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MATERIALS AND PROCESSES FOR SHUTTLE ENGINE, EXTERNAL TANK, AND SOLID ROCKET BOOSTER

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16. ABSTRACT

The Space Shuttle will provide a low cost delivery system for Earth orbital payloads by amortizing launch costs through system reusability. The Shuttle flight system is composed of the Orbiter, an External Tank (ET) that contains the ascent propellant to be used by the Space Shuttle Main Engines (SSME), and two Solid Rocket Boosters (SRB). The ET is expended on each launch; the Orbiter and SRB's are reusable. It is the requirement for reuse which poses the exciting new materials and processes challenges in the development of the Space Shuttle. This report deals with the materials and processes for the SSME, the ET, and the SRB. A brief description of the Space Shuttle and the mission profile is given. The Shuttle configuration is then described with emphasis on the SSME, ET, and SRB. The materials selection, tracking, and control system used to assure reliability and to minimize cost are described, and salient features and challenges in materials and processes associated with the SSME, ET, and SRB are subsequently discussed.

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I. INTRODUCTION

The accomplishments of the Space Program have been possible primarily because of the availability of highly reliable expendable launch vehicles and non-reusable spacecraft. However, the next generation space transportation system, the Space Shuttle, will provide a low cost delivery system for Earth orbital payloads by amortizing launch costs through system reusability. It is the reuse requirement which poses the exciting new materials and processes challenges in the development of the Space Shuttle.

The integrated Space Shuttle vehicle consists of the Orbiter, the External Tank (ET),[1] and two Solid Rocket Boosters (SRB).[2] The propulsive system for the Orbiter is composed of three 470 000 lb (2.09 MN) (vacuum thrust), reusable, high performance throttleable rocket engines burning liquid hydrogen (LH_2) and liquid oxygen (LOX), and referred to as the Space Shuttle Main Engines (SSME).[3] The reusable Orbiter can deliver into orbit single or multiple payloads of up to 65 000 lb (29.5 Kkg), with cargo bay capacity of 60 by 15 ft (18.3 by 4.6 m).

The ET contains the ascent propellant to be used by the SSME's and is the only major flight structure intended to be expendable. The SRB's provide thrust augmentation during the initial phases of the launch, up to a velocity of approximately 4600 ft/sec (1.4 km/s), and are recoverable by means of large parachutes. The combined sea level thrust of SSME's and SRB's is approximately 6.25 million lb (2.84 Mkg).

A brief scenario of a future Space Shuttle mission is as follows. The mission begins with the installation of the mission payload into the Orbiter payload bay. The SSME's and SRB's will fire in parallel for liftoff. The two SRB's

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NOTE: English units of measurement are to be used; metric units may be approximate.

1. Contractor — Martin Marietta Corporation.
2. Contractors — Thiokol Corporation and McDonnell Douglas Corporation.
3. Contractor — Rocketdyne Division of Rockwell International.

are jettisoned after burnout and are recovered after parachuting into the ocean. The ET is then jettisoned before the Orbiter has attained orbit. An orbital maneuvering system is then used for orbital insertion, orbit change, rendezvous, and the subsequent deorbiting thrust to return to Earth.

Payload bay doors in the Orbiter can be opened, allowing payload exposure or capture of any orbiting object if that is a requisite. After orbital operations of 7 days (30 days with additional consumables), deorbit and reentry into the Earth's atmosphere at a high angle of attack occur. At low altitude, the Orbiter then planes into horizontal flight for a typical high-performance type aircraft landing at approximately 185 kn (95.2 m/s) nominal. A 2-week ground turnaround is the approximate goal for reuse of the Orbiter.

This report deals with the materials and processes for the Space Shuttle elements, SSME, ET, and SRB, for which the George C. Marshall Space Flight Center (MSFC) has management and development responsibility. The detailed treatment of these major Space Shuttle elements begins with an overview of the materials selection, tracking, and control system employed by MSFC to provide that cohesiveness across these Shuttle elements so necessary to guarantee materials and processes uniformity with minimum cost, minimum documentation redundancy, and high reliability. A discussion of management information and control of Shuttle element materials and a detailed independent treatment of the salient features and challenges in materials and processes associated with SSME's, the ET, and the SRB's follow.

II. MATERIALS CONTROL FOR SSME, ET, AND SRB

Past experience has shown conclusively that a good materials control program is necessary to optimize reliability and minimize cost. Extensive experience with materials in the Redstone, Jupiter, Juno II, Saturn, and Skylab Programs has demonstrated conclusively the necessity to control the materials and associated processing used in critical space vehicle service. The ability to know all the materials in the system and to recall this information on demand are equally important. A fact all too frequently overlooked by nonaerospace critics of meticulous materials control is simply that the final commitment to Shuttle liftoff is irrevocable. There is no turning around on the runway, no last minute opportunity to change one's mind; things have to work right the first time on the

Shuttle. This is believed to be within the state-of-the-art, primarily through the establishment of the proper disciplinary controls at the outset (early in the preliminary requirements/design cycle).

An effective materials control system must accomplish the following tasks:

1. Identify materials and processes

2. Identify materials usages

3. Identify, evaluate, and eliminate materials dependent hazards[4]

4. Provide for waivers or deviations to materials and processes specifications, through the aegis of a Materials Application and Evaluation Board (MAEB)

5. Document all materials and processes decisions and associated rationale

6. Provide for information retrieval.

In the execution of this responsibility, some specific materials properties and characteristics are of special concern:

1. Material environmental compatibility:

   a. Compatibility with LOX or gaseous oxygen (GOX)

   b. Propellant compatibility

   c. Gaseous hydrogen (GH_2) embrittlement

   d. Hydraulic fluids/pressurization gases

   e. Coolant compatibility

2. Flammability (air)

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4. A material dependent hazard is defined as an occurrence that places either a person, the mission, or vehicle in jeopardy.

3. Toxicity (as related to production, or use, considering combustion, pyrolysis, etc.)

4. Corrosion and stress corrosion

5. Vacuum outgassing and contamination

6. Age/life

7. Properties and characterization.

The fundamental method by which materials are selected, tracked, and finally controlled at MSFC can be seen in the Materials Control Logic Diagram (Fig. 1). Note that waivers/deviations are submitted in triplicate by the contractor via a Materials Usage Agreement (MUA). MUA's requiring action by the MAEB are acted on by the Board in real time. Some potential waivers/deviations to the materials specifications are resolved without submittal to the Board when it can be shown that there really is no departure from specifications. Such an MUA is withdrawn by the contractor involved through mutual agreement. Only authentic MUA's are logged and tracked by the System. In actual practice, only very rarely does an MUA ever progress farther through the logic network than the output of the MAEB to the project manager and thence to the contractor. Because the project manager has representation on the MAEB, the Board decision is invariably final.

This system is employed at MSFC in the management of materials control for SRB, ET, and SSME. The adoption of a uniform system has already proved invaluable by providing concrete assurance and tangible proof that materials requirements are met, and uniformity and equitability of materials excellence are being maintained across the three Shuttle elements. Also, the system quite naturally fosters cross-fertilization and greatly enhances the systems material compatibility aspect.

To the casual observer, the structural method of control previously described may seem inordinate when superficially contemplated. However, the enormous variety of materials with their multitudinous stringent environmental requirements such as high pressures and temperatures, LOX and GOX compatibility, and a host of other integrated and synergistic influences necessitates an orderly, disciplined method of materials control. Nowhere in the three aforementioned Shuttle elements are the challenges in materials development more crucial or more evident than in the SSME.

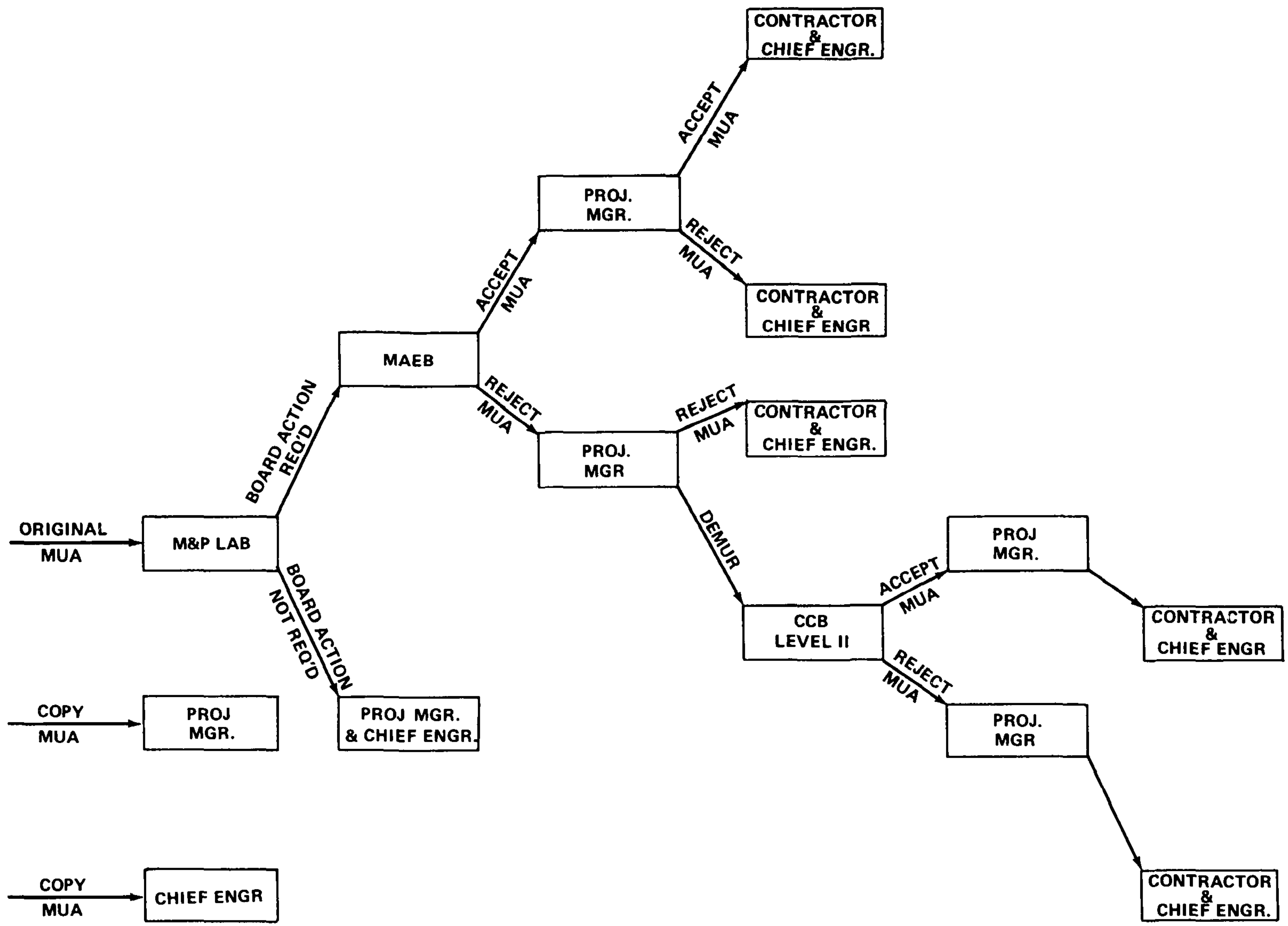

Figure 1. Materials control logic diagram.

III. SSME MATERIALS AND PROCESSES

The SSME is a reusable high performance liquid propellant rocket engine with variable thrust. Three SSME's are used to power the Orbiter, each burning approximately 8 min from launch through the vehicle boost period. Each SSME employs a staged combustion cycle to power the turbopumps and utilizes high combustion chamber pressure. The staged combustion cycle features partial propellant combustion first in the preburners at high pressure and relatively low temperature, then subsequently the propellants are completely combusted at high temperature and high pressure in the main chamber, before expanding through the high-area-ratio-nozzle. Figure 2 shows typical pressures, temperature, and propellant flow rates used.

The hydrogen fuel cools all combustion devices which are contacted by high temperature combustion products. The engine is controlled by an electronic controller which automatically performs the checkout, start, main stage, and engine shutdown functions. For flight, the three Orbiter SSME's operate in parallel with the SRB's during launch and then continue to burn until just before injection after SRB separation. Each of the engines operates at a mixture ratio (LOX/LH_2) of 6:1 and a chamber pressure of approximately 3000 psia (20.68 MPa) to produce a sea level thrust of 375 000 lb (1.67 MN) and a vacuum thrust of 470 000 lb (2.09 MN) with a fixed nozzle area ratio of 77.5:1. The engines are throttleable over a thrust range of 50 to 109 percent of the design thrust level. The throttleability feature allows a higher thrust level during liftoff and during the initial ascent period, and also provides the capability of limit Orbiter acceleration to 3 g's during the final period of the ascent. The engines are gimbaled to provide roll, pitch, and yaw control during the Orbiter boost phase. The engine gimbal angle capability is approximately ±10.5° (±0.184 rad) of pitch and ±8.5° (±0.149 rad) of yaw control.

The aspects of reusability and the high engine operating pressures and temperatures are prime technical drivers in the engine design and provide the bulk of the technical challenges associated with the engine development. The following are of considerable importance to the ultimate success of the engine:

1. Hydrogen environment embrittlement

2. LOX/GOX compatibility

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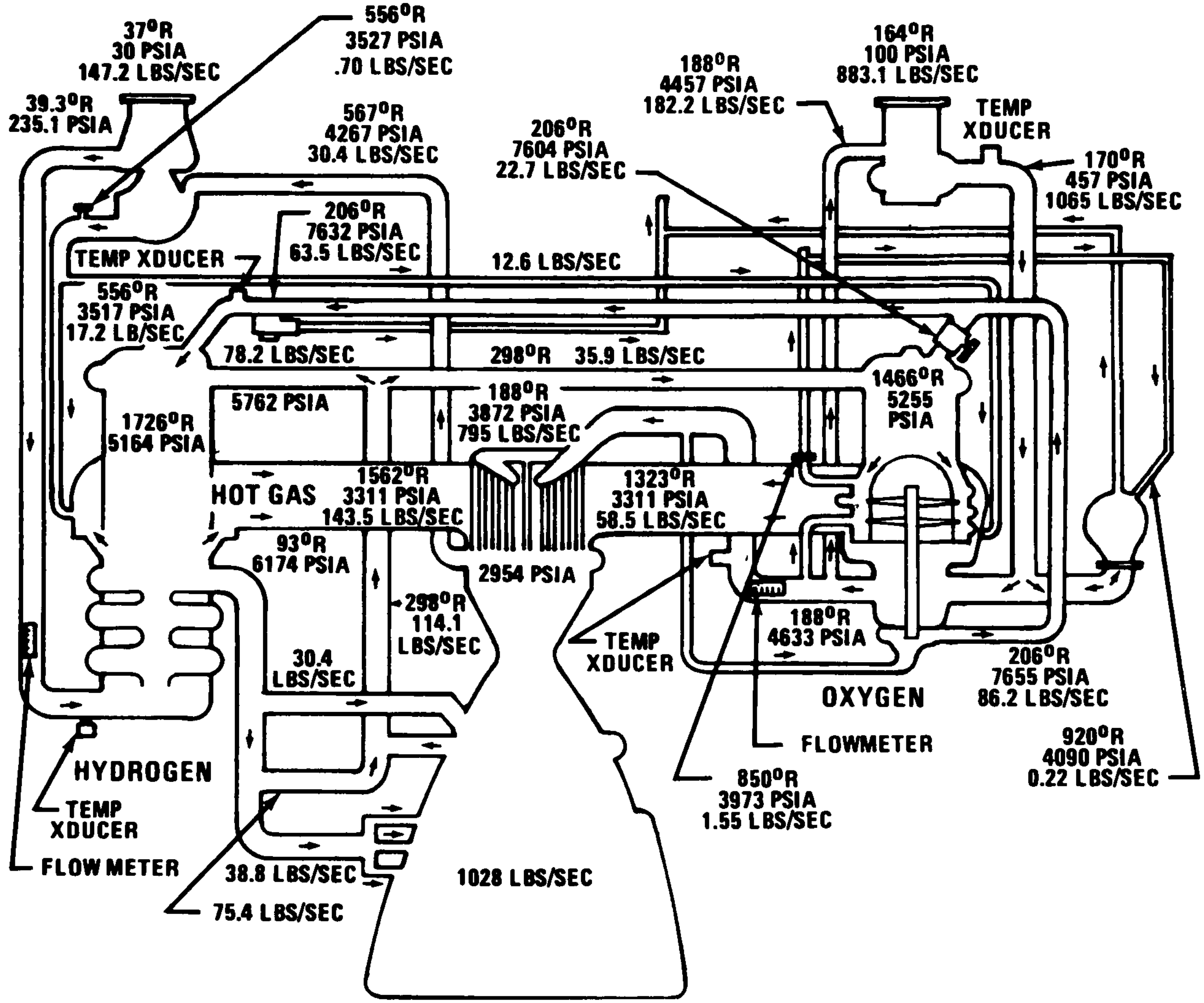

Figure 2. SSME propellant flow schematic.

3. Stress corrosion cracking

4. Hydraulic fluid testing and qualification.

More than 50 different alloys are used in construction of the SSME, many of them well established in the Aerospace Industry. However, some of the alloys are relatively new, with less accumulated backlog of experience, especially in the high pressure hydrogen environment. Table 1 gives examples of the type materials used and the related applications.

A. Hydrogen Environment Embrittlement

Many of the iron, nickel, and cobalt-based alloys are adversely affected by high pressure hydrogen in terms of reduced ductility, tensile strength, low cycle fatigue life, and increased crack growth rates when used in applications involving plastic strain.

Inexplicably and often, hydrogen environment embrittlement (HEE) effects do prove to be more pronounced at room temperature than at either higher or lower temperature. The graph of notch strength versus temperature for electroformed nickel shown in Figure 3 gives graphic evidence of this fact. An appreciable amount of electroformed nickel is used in the SSME.

The electroforming process has been developed to a high degree of perfection and is used extensively as a process to fabricate and bond SSME structural members. In fact, electrodeposited (ED) nickel is used to close out the NARLOY Z main combustion chamber liner; therefore, ED nickel resistance to HEE is of prime concern. The solution to the embrittlement problem in this instance proved to be the use of an ED copper coating process to protect the nickel.

Table 2 gives a compilation of notched strength data accumulated from work done by Pratt and Whitney, Rocketdyne Division of Rockwell International, and MSFC. In general, HEE appears in the presence of relatively high purity hydrogen and is more pronounced at room temperature and high pressure, is not time dependent, and disappears with no after effects upon removal of the hydrogen environment (provided there was no plastic strain while in the environment). The increased effect of HEE at high pressure, mentioned previously, is clearly depicted in a comparison of two materials used extensively in the

TABLE 1. SSME METALLIC MATERIALS

Material	Applications
Inconel 718	Valves, manifolds, structural shells, bellows, volutes, springs
Inconel 625	Face plates, vanes, acoustic rings, spark plug adapters
Rene 41	Bolts, screws
K-MONEL	Turbopump stations and rotors, housing covers
MAR-M246 (DS)	Turbine blades
MAR-M246 (CC)	Turbine Nozzles
Waspaloy	Disc, shafts
440C Stainless Steel	Thrust bearings, valve seats
2024 Aluminum	Retainer rings
Tens — 50 Aluminum	Volute housings, diffuser assemblies
NARLOY-Z	Thrust chamber liner
7075-T73	Pneumatic console housing
Armco 21-6-9	Spark plug housing, flow straighteners
Kovar	Adapters
Beryllium Copper	Bearing Assemblies
Ti-6Al-6V-25N	Gimbal bearing and ring
Ti-6Al-4V	Actuator strut, manifolds
Ti-5Al-2.5 SN	Impellers, valves
Silver-8 cu	Seals
304L	Injector elements, filters, connectors, assemblies
Narloy A	Baffles, ASI insert
Haynes 188	Liners, element sleeve, ASI nozzle, mounting flange rings, shells, flanges, brackets
347 CRES	Mixer tube, plate, plugs, rings
A-286	Coolant tubes, baffle element sleeve, nuts, washers, solenoid valve, body, shafts
Incoloy 903	Transition rings, HEE protection, strut ring, turbine shell, bellows housing, diffusers, transfer tube, sleeve assembly
321 CRES	Flowmeter, sleeves, and hubs
6061-76	Seal mounting plate, burst diaphragm
Egiloy	Springs
Inconel X-750	Seals
Alloy 713 LC	Nozzle turbine casting
Hastelloy B	Pump housing cartridges
302 CRES	Retainers, shims, and pins

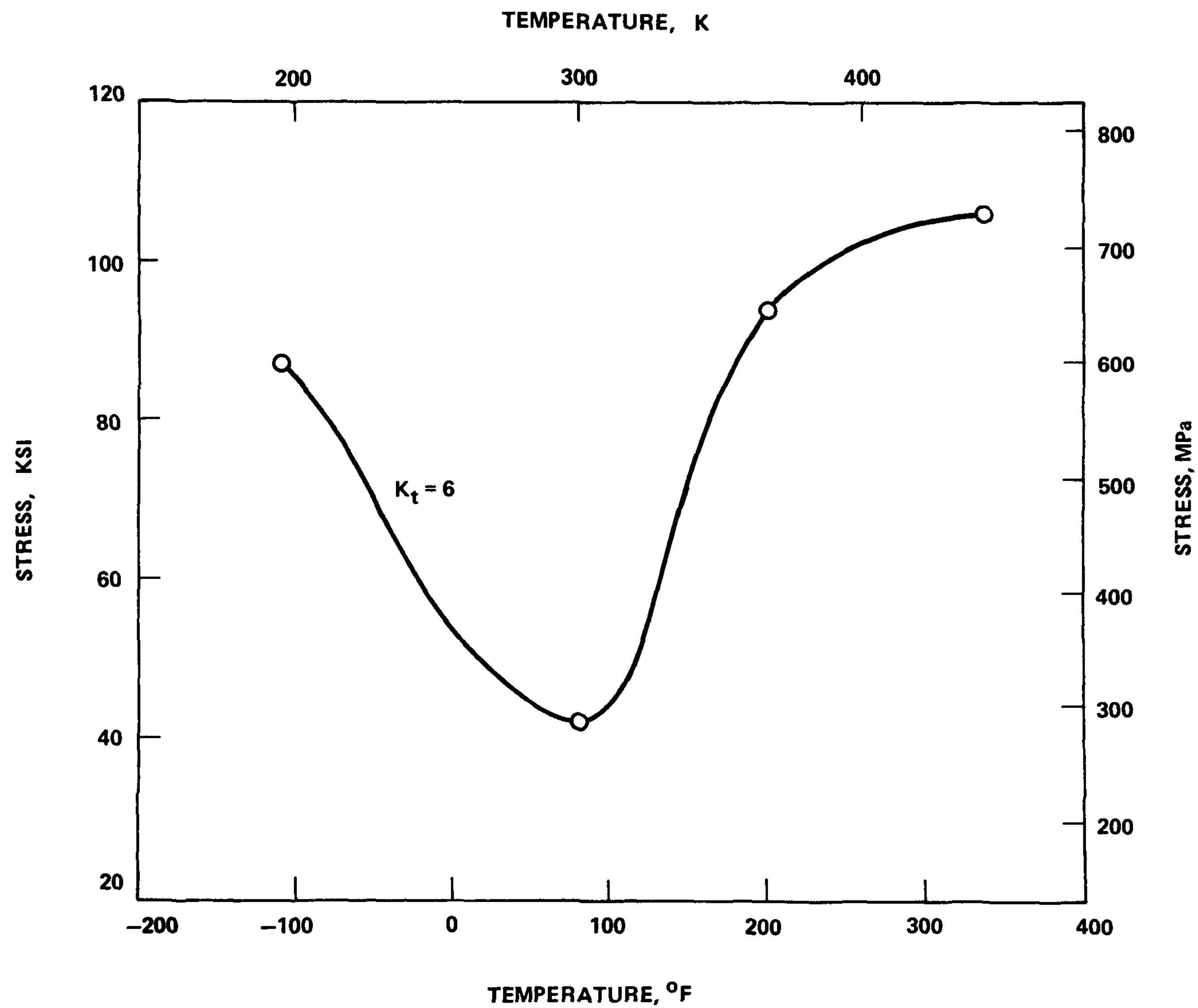

Figure 3. Notched strength versus temperature for electroformed nickel in 1200 psig (8.27 MPa) H_2.

TABLE 2. RELATIVE RESISTANCE TO HYDROGEN EMBRITTLEMENT NOTCHED STRENGTH RATIO (H_2/ He) FOR VARIOUS ALLOYS IN HYDROGEN AT ROOM TEMPERATURE

Alloy	K_t	Pressure ksi	(MPa)	Ratio H_2/He
250 Maraging	8	10	(68.95)	0.12
410	8	10	(68.95)	0.22
1042 (Q& T)	8	10	(68.95)	0.22
17 7 PH (TH 1050)	8	10	(68.95)	0.23
HP 9-4-20	8	10	(68.95)	0.24
H-11	8	10	(68.95)	0.25
Inconel X-750	6.3	7	(48.3)	0.26
Rene 41	8	10	(68.95)	0.27
ED Nickel	8	10	(68.95)	0.31
4140	8	10	(68.95)	0.40
Inconel 718	8	10	(68.95)	0.46
MP 35N	6.3	10	(68.95)	0.50
440 C	8	10	(68.95)	0.50
Ti-6 Al-4 V (STA)	8	10	(68.95)	0.58
Monel 400	6.3	7	(48.3)	0.65
D 979 Stainless	6.3	7	(48.3)	0.69
Nickel 270	8	10	(68.95)	0.70
CG 27 Stainless	6.3	7	(48.3)	0.72
A 515-G70	8	10	(68.95)	0.73
HY 100	8	10	(68.95)	0.73
A 372-IV	8	10	(68.95)	0.74
1042 (Normalized)	8	10	(68.95)	0.75
Inconel 625	8	5	(34.5)	0.76
A517-F (T-1)	8	10	(68.95)	0.77
A 533-B	8	10	(68.95)	0.78
Ti-6 Al-4 V (Ann.)	8	10	(68.95)	0.79
1020	8	10	(68.95)	0.79
HY 80	8	10	(68.95)	0.80
Inconel 706	6.3	7	(48.3)	0.80
Ti-5 Al-2.5 Sn ELI	8	10	(68.95)	0.81
Armco Iron	8	10	(68.95)	0.86
304	8	10	(68.95)	0.87
321	8	5	(34.5)	0.87
Hastelloy X	8	5	(34.5)	0.87
305	8	10	(68.95)	0.89
Astroloy	8	5	(34.5)	0.90
347	8	5	(34.5)	0.91
Haynes 188	6.3	7	(48.3)	0.92
304 N	6.3	5	(34.5)	0.93
310	8	10	(68.95)	0.93
Be-Cu (Alloy 25)	8	10	(68.95)	0.93
RA 330	6.3	7	(48.3)	0.95
A-286	8	10	(68.95)	0.97
21-6-9	6.3	7	(48.3)	0.97
7075-T73	8	10	(68.95)	0.98
6061-T6	8	10	(68.95)	1.00
OFHC Copper	8	10	(68.95)	1.00
316	8	10	(68.95)	1.00
Incoloy 903	8	5	(34.5)	1.00

SSME. Incoloy 903 is a corrosion and heat resistant age-hardenable iron-nickel-base alloy, while Inconel 718 is a wrought, age-hardenable nickel-base alloy. Figure 4 shows the relative performance of these two alloys with regard to crack growth rate at various stress intensities and at room temperature (highest temperature susceptibility). Note that the iron base alloy 903, in this instance, shows far less pressure dependency than the nickel-base alloy 718; therefore, it does not generally require the coatings and protective overlay of a material such as Incoloy 88. The design strategy to avoid the debilitating effects of GH_2 embrittlement has been to:

1. Use nonsusceptible materials where possible

2. Avoid plastic strain (notches, sharp fillets, etc.)

3. Use appropriate processes to provide an overlay or coating of non-susceptible material.

Although the basic embrittlement mechanism is by no means well understood, ways and means of circumventing its harmful effects on material properties have been devised. This is done frequently by appropriate coating or plating operations in the manufacturing processes and by the other design stratagem previously noted, i.e., keeping design stresses low enough to avoid plastic strain.

B. LOX/GOX Compatibility

LOX/GOX materials compatibility has been a persistent specter in rocket propulsion systems since the beginning. The recorded history of LOX/GOX material compatibility testing at MSFC dates back to the mid-50's when Lucas and Riehl [1] at the Army Ballistic Missile Agency developed an instrument for acquisition of impact sensitivity data for use by designers then designing the first Saturn space vehicles. At that time, an impact sensitivity specification called MSFC-SPEC-106 was also developed which, together with its successors, has been the primary LOX/GOX materials compatibility regulatory means employed during the design of the Saturn vehicles. The Apollo 13 incident was the crucial happening in NASA which pointed up the urgent requirement for further research on LOX/GOX compatibility at high pressure. In that event, a Teflon-fueled LOX/GOX fire in the No. 2 supercritical O_2 tank caused tank rupture in the CSM of the Apollo 13 approximately 55 hr after liftoff, while

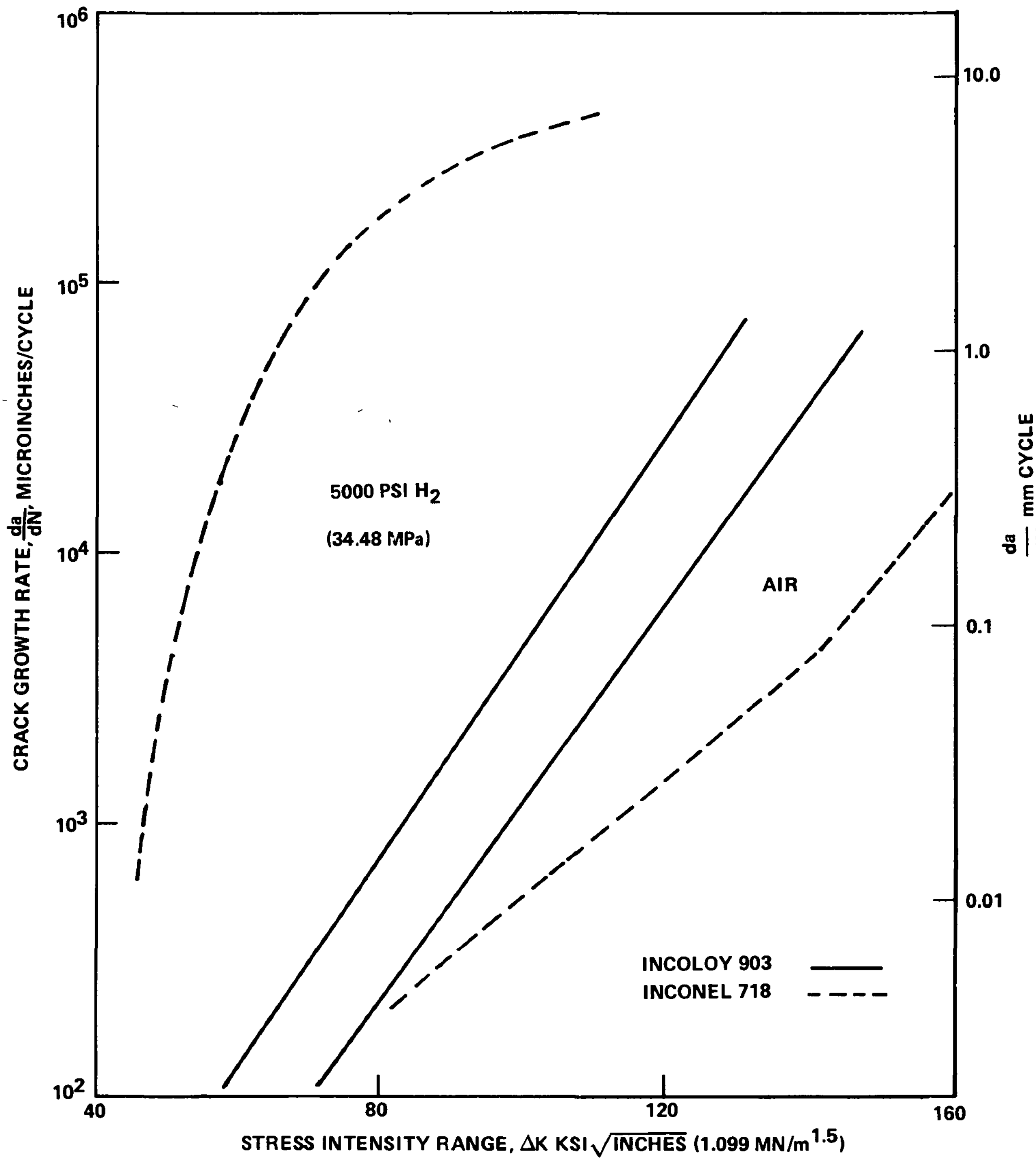

Figure 4. Crack growth rate, da/dN, versus stress intensity range, ΔK, for Incoloy 903 and Inconel 718 in air and 5000 psi (34.48 MPa) hydrogen at room temperature with a 9 min load time cycle (simulated SSME cycle).

enroute to the Moon. The extensive failure investigations subsequently conducted gave some unprecedented insight into the next generation of problems to be solved in the operation of the even higher pressure LOX/GOX systems used on SSME [2]. This insight led directly to the development of a 10 000 psia (68.95 MN/m^2) tester built to MSFC specified requirements by the Rocketdyne Division of Rockwell International [3]. This tester incorporated many new features such as the balanced striker, oscilloscope and digital monitoring of plummet velocity, material reaction via photocell flash, load cell response (measuring energy to the sample), sample temperature, and cell pressure.

In developing materials LOX/GOX compatibility design data, the high pressures used in the SSME have necessitated a departure from the previous low pressure criterion of "go-no go." That is, in some applications, materials tested at the high anticipated-use pressures do not meet the former straightforward low pressure impact sensitivity criterion of 10 kg-m (98 J) energy delivered to the test specimen. It has been necessary to evaluate the materials' LOX/GOX threshold energy density rate (E^*) at representative use pressure, temperature, and material thickness. Further, the threshold energy density rate is then used to determine a figure of merit by dividing E^* by the energy density rate reasonably attainable in the component in question. This gives one a "figure of merit" on which to judge the application, but it is not precisely correct to refer to this number as a safety factor. The term "safety factor" in the commonly used structural design context is considered inappropriate to describe the calculated figure of merit, since there cannot be that same degree of precision in the absolute magnitude of the figure of merit number. Materials, metallic and nonmetallic, are assessed on this basis for the critical very high pressure and temperature applications. In certain special cases, effects such as adiabatic compression and cavitation are also taken into account.

Figure 5 shows the precise decision logic used in the accurate determination of a material threshold energy. This is then convertible into the energy density rate parameter E^* by knowing the test specimen modulus and the plummet deceleration rate. For reference purposes the standard 10 kg-m (98 J) drop in a standard tester equates to an E^* of approximately 2.4×10^6 ft-lb/in.^{2}/sec (16.55 $GN/m^2/s$).

Table 3 shows some of the recent test data relating effects of high pressure and material thickness to impact threshold sensitivity energy for some of the more important nonmetallic materials used in the SSME. These data show an increased sensitivity with increasing pressure and decreased sensitivity with

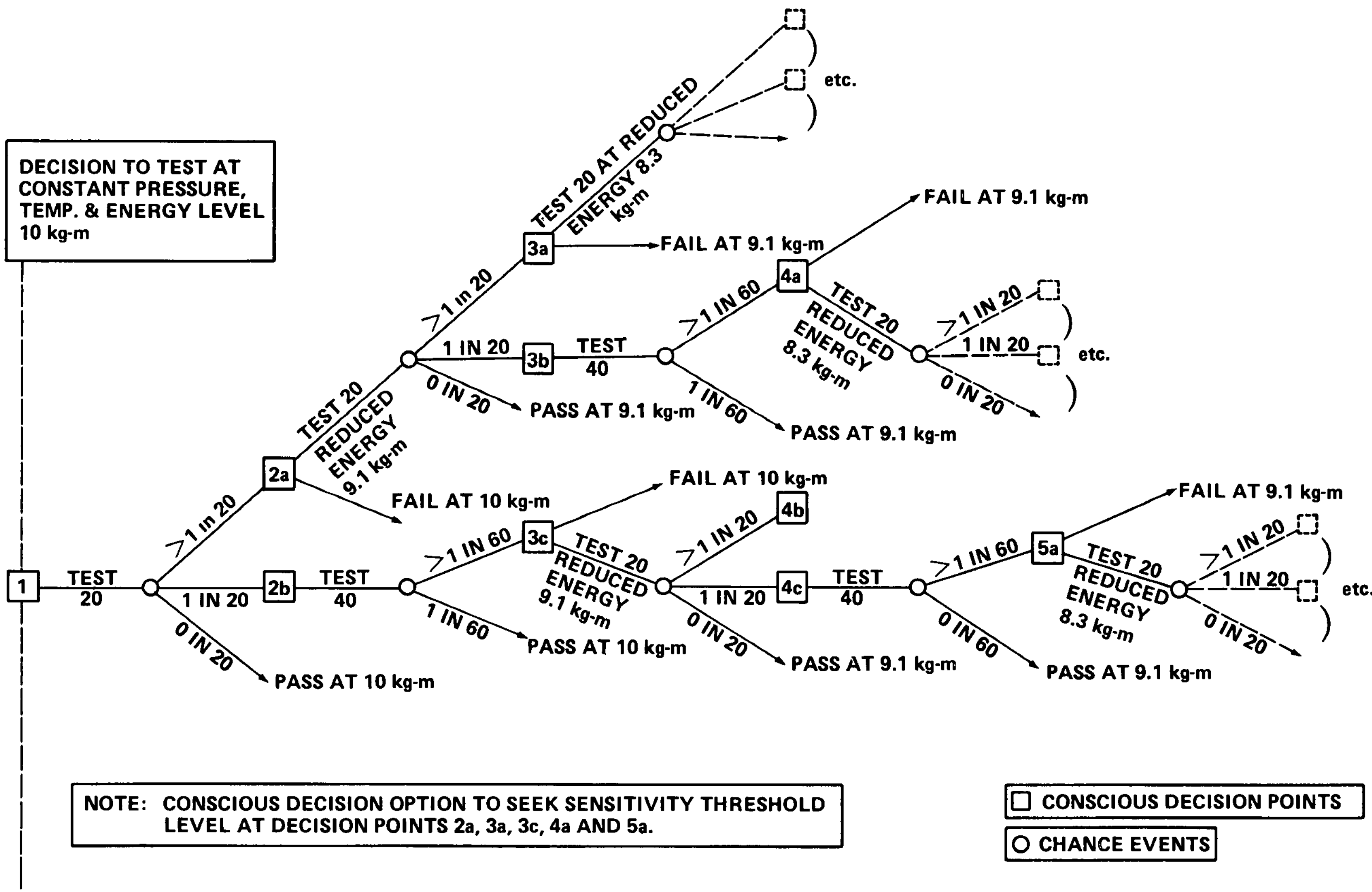

Figure 5. Decision logic diagram for LOX/GOX impact sensitivity threshold determination.

TABLE 3. EFFECTS OF PRESSURE AND MATERIAL THICKNESS ON IMPACT THRESHOLD SENSITIVITY ENERGY FOR SELECTED NONMETALLIC MATERIALS IN LOX

Material	Thickness		Pressure		Threshold Energy	
	in.	(mm)	psia	(MPa)	kg-m	(J)
CTFE	0.053	(1.346)	1500	(10.34)	10	(98.04)
CTFE	0.050	(1.270)	8800	(60.68)	< 6	(58.82)
CTFE	0.125	(3.175)	8800	(60.68)	<10	(98.04)
PTFE	0.050	(1.270)	1500	(10.34)	10	(98.04)
PTFE	0.050	(1.270)	5500	(37.92)	9	(88.24)
PTFE	0.050	(1.270)	8800	(60.68)	8	(78.43)
PTFE Glass	0.100	(2.540)	500	(3.45)	10	(98.04)
PTFE Glass	0.100	(2.540)	5200	(35.85)	3	(29.41)
15% PTFE Glass	0.050	(1.270)	1500	(10.34)	10	(98.04)
15% PTFE Glass	0.050	(1.270)	8800	(60.68)	5	(49.02)
Mineral Filled PTFE	0.062	(1.575)	1500	(10.34)	10	(98.04)
Mineral Filled PTFE	0.062	(1.575)	5000	(34.48)	6	(58.82)
FEP	0.050	(1.270)	1500	(10.34)	10	(98.04)
FEP	0.050	(1.270)	8800	(60.68)	6	(58.82)
FEP	0.125	(3.175)	9000	(62.06)	10	(98.04)

increased material thickness. Both results are explainable on the basis of increased energy density per unit time. As previously noted, if the rate of energy absorption is a variable, then E* will increase or decrease accordingly, a factor which must ultimately be accounted for in analyzing components using the factor of merit calculation method.

Other test data indicate that almost all the metallic materials used in the SSME are insensitive to the 10 kg-m (98 J) energy level in either LOX or GOX at pressures up to at least 8000 psi (55.16 MPa) and at the anticipated use temperatures. Therefore, the high pressure effect on LOX/GOX sensitivity has been carefully explored for the range of applications anticipated in the SSME, and workable solutions have been developed accordingly.

C. Stress Corrosion Cracking

In past space vehicle and engine development programs, one of the most insidious problems has been stress corrosion cracking (SCC) of certain alloys. The insidious aspects of SCC has to do with the propensity for the cracking to progress undetected inside holes, under attachments, and at other virtually uninspectable locations where the combined action of corrosion and static tensile stress conspired to produce brittle fracture. Nearly all metal systems extensively used in aerospace vehicle design contain one or more alloys susceptible to SCC in some environment. Unfortunately, the higher the strength, the greater the susceptibility to SCC. Like the siren Lorelei, the lure and enticement of superior strength seemingly continue to bewitch designers into the selection of SCC susceptible alloys, in spite of the attendant risk.

In full recognition of this inherent tendency, Design Criteria for Controlling Stress Corrosion Cracking, MSFC Document (10M33107B), was prepared at the Marshall Center [4] to clearly define and control the use of alloys with respect to SCC. This is the controlling SCC document not only for the SSME development but for the ET and the SRB as well. The document is so written to group alloys into three main categories or tables:

1. Alloys with high resistance to SCC

2. Alloys with moderate resistance to SCC

3. Alloys with low resistance to SCC.

Only materials for which there is a statistically meaningful body of SCC data available are presented in these tables. The use of materials other than those listed requires appropriate substantiating data before any use is permitted, and then only through the submittal and approval of an MUA. In spite of a sustained effort to purge susceptible materials entirely from the system, one inevitably finds a few isolated cases where a specific property is so crucial in that specific application that SCC must be eliminated by some other stratagem and a susceptible material must be used. When such a case of dire necessity to use a SCC susceptible material arises, an MUA must be submitted with the following information:

1. Combination of all tensile service stresses (sustained structural, assembly, handling, etc.), when additive, must be less than the threshold stress for SCC.

2. Component is hermetically sealed or totally immersed in nonmoisture-bearing oil in a sealed system.

Only a very few examples come to mind where SCC susceptible alloys must be used; the most notable is the use of 440C steel in bearings where there is a requirement for high hardness and where the wear characteristics of the material are superior to any other contender. Occasionally, a precipitation hardening alloy must be used where high temperature heat treatment processes cannot be employed. In such cases, adequate precautions must be taken to prevent excessively high assembly or use stresses and to protect the material from moisture or other agressive media. The list of parent materials with high resistance to SCC at ambient temperature, in or around salt water (alternate immersion), is quite impressive (Table 4). Weldments present a more difficult problem, and data are not as extensive in this case, although there are good data for aluminum alloys and selected stainless steels in the 300 series.

Unlike the Lorelei, I do not propose to entice the reader-designer by printing in this report the list of moderate and highly susceptible alloys. Those with legitimate justification will no doubt acquire, or already have, a copy of the MSFC 10M33107B document. In the SSME, predominantly non-SCC-susceptible materials have been used, but where departures have been absolutely necessary, then the previously noted use criteria have been relied upon.

TABLE 4. ALLOYS WITH HIGH RESISTANCE TO STRESS CORROSION CRACKING

Steel and Nickel Alloys			
Alloy	Condition	Alloy	Condition
Carbon Steel (1000 Series)	Below 180 ksi (1241 MPa) YS	PH 13-8 MO Stainless Steel	H1000 and above
Low Alloy Steel (4130, 4340, D6AC, etc.)	Below 180 ksi (1241 MPa) YS	15-5 PH Stainless Steel	H1000 and above
Music Wire (ASTM 228)	Cold drawn	17-4 PH Stainless Steel	H1000 and above
HY-80 Steel	Quenched and tempered	PH 14-8 Stainless Steel	CH900 and SR 11950 and above
HY-130 Steel	Quenched and tempered	PH 15-7 MO Stainless Steel	CH900
HY-140 Steel	Quenched and tempered	17-7 PH Stainless Steel	CH900
1095 Spring Steel	Quenched and tempered	Hastelloy C	All
300 Series Stainless Steel (Unsensitized)[a]	All	Hastelloy X	All
21-6-9 Stainless Steel	All	Incoloy 901	All
Carpenter 20 CB Stainless Steel	All	Incoloy 903	All
Carpenter 20 CB-3 Stainless Steel	All	Inconel 718	All
A286 Stainless Steel	All	Inconel X-750	All
AM350 Stainless Steel	SCT 1000 and above	Ni-SPAN-C 902	All
AM355 Stainless Steel	SCT 1000 and above	René 41	All
ALMAR 362 Stainless Steel	H1000 and above	Unitemp 212	All
Custom 455 Stainless Steel	H1000 and above	Waspaloy	All

Aluminum Alloys			
Wrought[b]		Cast	
Alloy	Condition	Alloy[f]	Condition
1000 Series	All	319.0, A319.0	As cast
2011	T8	333.0, A333.0	As cast
2024	T6[c] T8[d]	355.0, C355.0	T6
2219	T6, T8	356.0, A356.0	All
3000 Series	All	357.0	All
4032	T6	B358.0 (tens-50)	All
5000 Series	All[e]	359.0	All
6000 Series	All	380.0, A380.0	As cast
7075	T73	A612.0, C612.0	As cast
7475	T73	514.0 (214)	As cast
		518.0 (218)	As cast
		535.0 (Almag 35)	As cast

Miscellaneous Alloys			
Wrought		Cast	
Alloy	Condition	Alloy	Condition
Beryllium, S-200C	Annealed	Magnesium, ZK51A	All
HS 25 (L605)	All		
HS 188	All		
MP35N	All		
Titanium, 6Al-4V	All		
Titanium, 13V-11Cr-3Al	All		
Magnesium, M1A	All		
Magnesium, LA141	All		
Magnesium, LAZ933	All		

a. Including weldments of 304L, 316L, 321 and 347
b. Mechanically stress relieved (TX5X or TX5XX) where possible, including weldments of the weldable alloys.
c. Except plate and forgings which have low resistance.
d. Except forgings which have low resistance and plate which has moderate resistance.
e. High magnesium content alloys 5456, 5083, and 5086 should be used only in controlled tempers for resistance to SCC and exfoliation, these alloys are not recommended for high temperature application [150°F (65°C) and above].
f. The former designation is shown in parenthesis when significantly different.

D. SSME Hydraulic Fluid MIL-H-83282

As can be seen in Figure 2, the higher operating pressures in the SSME have been accompanied by higher operating temperatures as well. The requirement for higher operating engine temperatures and reusability and safety consideration prompted a critical assessment of the old standby hydraulic fluid (MIL-H-5606), a straight hydrocarbon material used so successfully in the Saturn program. Coincidentally, a "new" fluid, MIL-H-83282, a synthetic hydrocarbon, was under development by the DOD, reportedly for use as a more fire resistant, higher temperature replacement for the older fluid. Properties data for the MIL-H-83282 fluid were gathered and assessed for SSME and Shuttle Orbiter applicability, and it became apparent that the fluid could not, at that time, be considered completely characterized for use in the SSME hydraulic system, especially in the following four specific areas:

1. Lubricity

2. Corrosion and stress corrosion

3. Elastomer and seal compatibility

4. Sustained operation in the 275° to 300°F (408 to 422 K) range.

Subsequently, test data showed that the MIL-H-83282 fluid was superior to the MIL-H-5606 fluid with regard to lubricity, especially under high pressure load conditions. Extensive corrosion testing revealed negligible weight loss from metallic samples in air and in a nitrogen atmosphere blanket environment around the fluid in which the samples were immersed. Testing of soft goods such as Buna N and Viton revealed that Buna N withstood a temperature of 212°F (373 K) for 1 year quite well, and the Viton retained good properties for 180 days at a temperature of 300°F (422 K), a temperature much higher than any anticipated for use in the SSME. In testing for oxidation characteristics at 275° to 300°F (408 to 422 K), it became apparent that the MIL-H-83282 fluid was much less affected when the fluid was deaerated and operated in a sealed system. Under these conditions, the fluid performed quite well at the 275°F (408 K) operating temperature with virtually no degradation of properties.

A comparison of pertinent properties of the older MIL-H-5606 material and the newer MIL-H-83282 material can be seen in Table 5. Particularly noteworthy from a safety viewpoint are the favorable flash point, fire point, and autoignition temperature.

TABLE 5. TYPICAL PROPERTIES OF HYDRAULIC FLUIDS

	MIL-H-5606	MIL-H-83282
Kinematic Viscosity, cs ($\mu m^2/s$)		
At 300°F (422 K)	2.36 (2.36)	1.89 (1.89)
At -40°F (233 K)	488 (488)	2100 (2100)
Flash Point, °F (K)	209 (371)	410 (483)
Fire Point, °F (K)	230 (383)	495 (530)
Autoignition, °F (K)	460 (511)	640 (611)
Pour Point, °F (K)	<-75 (214)	-85 (208)
Specific Gravity, gm/cm^3 (kg/m^3)	0.8681 (868.1)	0.8433 (843.3)
Rubber Swell %		
72 hr at 725°F (408 K)	-	11.7
Bulk Modulus Isothermal Secant, psi (MPa)		
At 4000 psig (27.58 MPa)	212 000 (1462)	236 000 (1627)
Bulk Modulus Adiabatic, psig (MPa)		
500-3000 at 75°F (3.45-20.7 at 297 K)	260 700 (1798)	265 000 (1827)
500-3000 at 275°F (3.45-20.7 at 408 K)	200 900 (1385)	182 000 (1255)
Specific Heat (c), Btu/lb-°F (J/g-K)		
At 100°F (311 K)	0.465 (1.95)	0.499 (2.09)
At 300°F (422 K)	0.590 (2.47)	0.598 (2.50)

TABLE 5. (Concluded)

	MIL-H-5606	MIL-H-83282
Thermal Conductivity K, Btu-ft/hr-ft^2-°F (W/m-K)		
At 100°F (311 K)	0.079 (0.137)	0.097 (0.168)
At 300°F (422 K)	0.076 (0.131)	0.096 (0.166)
Vapor Pressure ASTM, Isoteniscope, mm		
At 100°F (311 K)	0.6	0.6
At 300°F (422 K)	56.0	7.8
Vacuum Exposure		
7 days at 2.5×10^{-6} torr (3.33 MPa)		
Weight loss, %	89.7	8.9
Residue	Tacky	Oily
4-Ball Test Data, mm		
1 kg Load	0.20	0.15
10 kg Load	0.25	0.24
40 kg Load	0.63	0.37

E. SSME Processing in General

The SSME is fabricated and assembled largely by welding and brazing of the wrought and cast components. Extensive and unique use of electron beam welding techniques is evident, but gas tungsten arc (TIG) welding is also used. Inertia welding is used to weld the oxidizer "posts" into the main injector body. The brazed assemblies are predominantly furnace brazed in a hydrogen environment, using noble-metal braze alloys to join Inconels 625/718, A-286, and Haynes 188. Overlays or surface barriers to hydrogen are provided by gold and copper platings of only 0.002 in. (0.051 mm) thickness, and Incoloys 88 and 903 are used extensively in the form of weld bead overlays. The corrosion and heat resistant age-hardenable iron-nickel-base alloy Incoloy 903 is used extensively because of its low thermal expansion, low elastic modulus, high strength, and resistance to HEE. Inconel 718, a vacuum melted austenitic precipitation hardened nickel-chromium base superalloy with excellent corrosion resistance, is also used extensively and is overlaid largely with the Incoloy 903 during processing to provide protection for HEE where temperatures above approximately -100°K (200 K) are expected, or where strains greater than approximately 0.5 percent will exist. Unquestionably, the manufacturing of the SSME represents one of the most challenging opportunities currently existing in the field of aerospace hardware.

IV. ET MATERIALS AND PROCESSES

The ET contains all the propellants supplied to the Orbiter main engines (LOX and LH_2). The fluid controls and valves for the main propulsion system are located in the Orbiter to reduce recurring costs. Antivortex and slosh baffles are mounted in the oxidizer tank to minimize liquid residuals and to damp fluid motion. The ET is 28 by 155 ft (8.5 by 47.2 m) and weighs 73 881 lb (35 512 kg) empty. It is currently planned for the ET to contain approximately 1.5 million lb (0.68 Mkg) of propellant. The forward LOX tank holds 1.3 million lb (0.59 Mkg) of LOX and the volumetrically larger rear tank holds 0.2 million lb (0.09 Mkg) of LH_2. The ET system is the only expendable element of the Space Shuttle and is jettisoned after the Orbiter has consumed the required fuel before achieving orbital velocity. The ET breaks up as it tumbles back through the atmosphere into an ocean impact area. The ET weight at main engine cutoff (MECO) is 78 807 lb (35 746 kg) (dry weight plus residual propellants) as presently planned. The materials and processes required to fabricate this unique "drop tank" will now be discussed in some detail.

A. ET Welding and Fracture Mechanics

The ET is primarily a welded structure, fabricated predominantly of aluminum alloy 2219. Saturn space vehicle manufacturing experience has been invaluable in providing the insight required to assure better weld quality with less repairs. Indeed, that experience plus the diligent weld materials properties and characterization work conducted in parallel, coupled with the coming-of-age and general acceptance of fracture mechanics, has laid the ground work for deliberate, calculable quality level, and optimization of manufacturing cost in the fabrication of the ET. The evolution of the current ET design and manufacturing philosophy is a lucid example of one of the salient characteristics of the aerospace industry— learning by, and building on, past experience thereby greatly enhancing future designs.

Capitalizing heavily on the past beneficial experiences with aluminum alloy 2219 on Saturn space vehicles, a large portion of the ET is composed of that alloy. Aluminum alloy 2024 is used also with due consideration given in the tank design to the somewhat reduced notched/unnotched tensile strength ratio at cryogenic temperatures, and nonstress corrosion cracking susceptible tempers and material forms of 2024 alloy have been used almost exclusively. Table 6 shows the major metallic materials used in the ET together with the appropriate applications. The materials selected and the associated processing have been strongly influenced by previous Saturn experience and by the early decision to capitalize on the accumulated fracture mechanics knowledge and experience.

Many of the Saturn V welds in 2219 alloy were made in a horizontal position, a condition which aids and abets the formation of weld porosity by entrapment of oxides and gas. A comprehensive analysis of accumulated weld data near the end of the Saturn Program in the late 1960's indicated that the major contributor to welding problems had indeed been weld porosity. As a consequence, a detailed study was initiated with the objective of determining very precisely the true nature of weld strength degradation as a result of weld porosity for a wide range of conditions [5]. The results of this extensive investigation are shown in Figure 6. Here we see statistical proof that the percentage of accumulative pore area in the cross-sectional plane of the test specimen bears a very strong linear relationship with the ultimate tensile strength. In fact, the relationship is so pronounced it is cardinal, having a linear regression correlation coefficient (γ) which exceeded -0.900, with the square of the correlation

TABLE 6. SPACE SHUTTLE ET METALLIC MATERIALS

Material	Applications
A356	Lightning rod
2024[a]	Tank baffle webs, stiffeners, angles and stringers, ring frames, chords, frame stabilizers, skin and stringers, panels buttstraps and flanges
2219	Tank and ogive gores, fittings, T-rings, tank band panels, lugs, ring frames, caps, covers, fittings, longerons, frame stabilizers, thrust panels, struts, channels, crossbeams, bulkheads, brackets, stiffeners, and braces
6061	Nose cap skins, frames and doubles
6063	Skin and stringer panels
7075[b]	Panel I-beams, longerons, ring frames, beam chords, webs, stiffeners, bulkheads, thrust fittings and struts
T:5Al-2.5 Sn	Strut fittings, spindle housings, and tank fittings
Inconel 718	Spindles
MIL-S-22499B	Shims
T:5648A	Tie plates

a. Design allows for reduced notch/unnotched tensile strength ratio at cryogenic temperatures and some small application of moderately SCC susceptible T851 plate, based on short transverse stresses being below SCC threshold stress.

b. Alloy is not used in any application at temperature colder than -200°F (144 K) in recognition of reduced notch-to-unnotched tensile strength below -200°F (144 K) and is used either in non-SCC susceptible tempers or in applications where short transverse stress is below the SCC threshold stress.

coefficient being in excess of 0.81. It should be noted, however, that the results of this analysis would not be appropriate for severe linear, or string, porosity. The results do apply to discrete porosity, however, which almost always predominates. To capitalize on this knowledge and the prior welding experience, two important changes were made for the ET:

1. Porosity limits were relaxed.

2. Excellent welding tooling, designed to utilize down-hand welding, was developed, thereby, greatly minimizing the incidence of porosity.

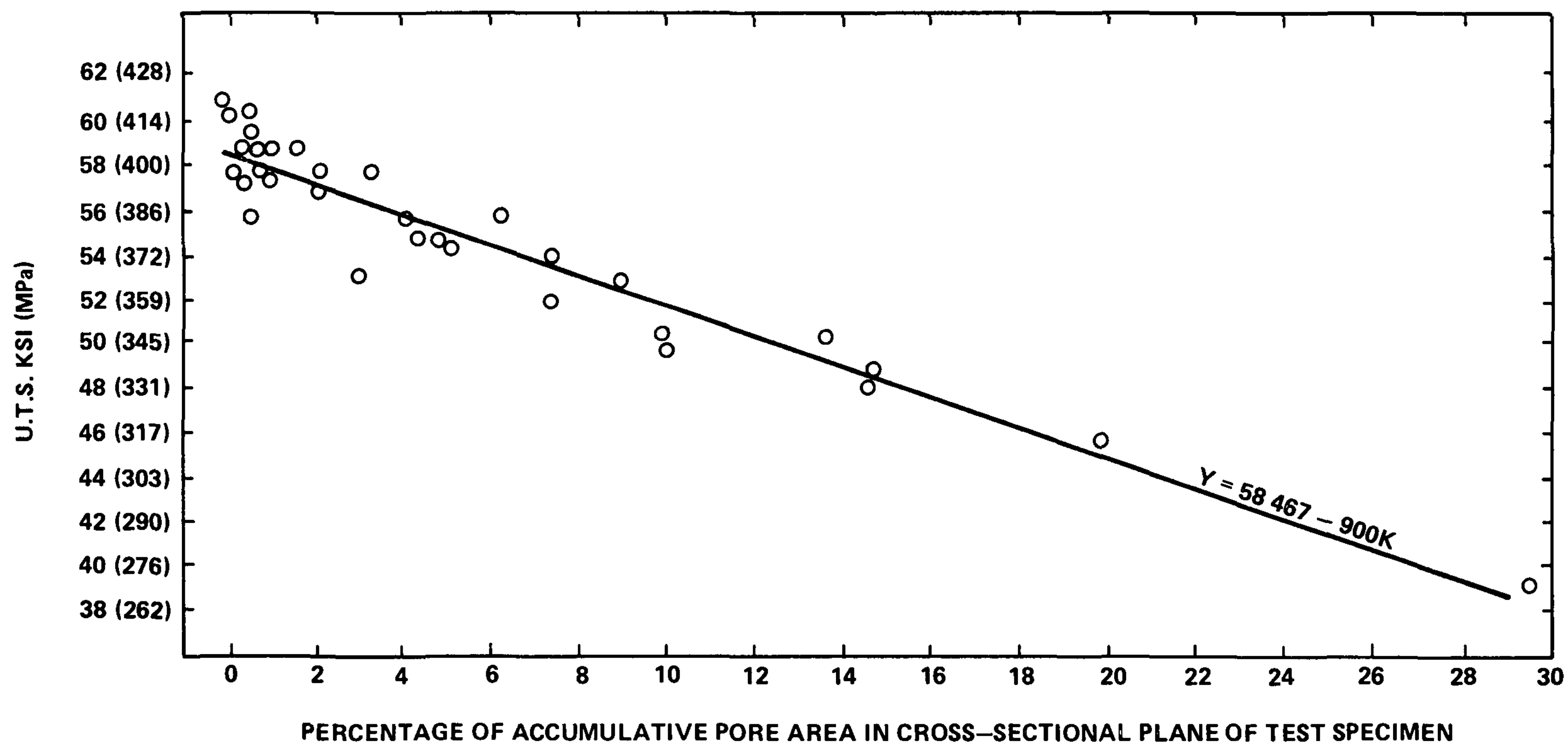

Figure 6. Cryogenic, -320°F (-78 K), ultimate tensile strength of flush bead TIG weldments in alloy 2219-T87, 0.250 in. (6.35 mm) plate, versus percentage of accumulative area in porosity in cross-sectional plane.

The Martin Marietta Corporation at the NASA Michoud Plant in New Orleans has designed and is using some of the most rigid and highest precision aluminum welding tooling ever used in any aerospace program; preliminary results already show the wisdom of the previously noted changes.

Figure 7 shows the ET LH_2 barrel trim-and-weld fixture and gives graphic evidence of the design consideration given to rigid positive tooling. Note that the welding of the barrel section longitudinal weld is done in the inside, down-hand position at the 6 o' clock location. This fixture trims the edges of the eight skin panels per barrel section to be welded. The barrel is rotated in a horizontal position to index each seam sequentially under the weld head, located on the bottom inside of the assembly.

The "opportunity cost" of the noted tooling pales into insignificance when the full advantage of the new welding approach is realized. This effects tremendous savings in subsequent radiographic inspection costs. It is intended to radiograph all welds during the design development test and evaluation period, involving six ET' s. Subsequently, only fracture critical welds will be radiographed. For the purposes of this discussion, a fracture critical weld is defined as one in which the critical flaw size is less than the thru-weld cross section thickness. The statistical validity of this approach will be verified by a careful analysis of the 100 percent radiographic results during the development phase, involving the fabrication of the first six tanks, before the production tanks are begun.

The fracture mechanics testing approach employed on ET consists of precracking appropriate specimens and then proof-stressing them to the point where penetration, or fracture, is imminent. The specimens are then cycled under operating conditions (stress and temperature profile) to simulate actual operating conditions and proof factor being evaluated. Specimens pass the test when they survive 12 operating cycles; the design requirement is three cycles with a scatter factor of four. Design and verification test requirements for the ET overall structure are 1.40 safety factor on ultimate and 1.50 safety factor on ultimate for pressure vessels with a scatter factor of four.

The fracture mechanics approach has also resulted in the "grading" of welds. Twenty-one grades of welds have been established, each of which has an associated allowable defect length for a single defect. For pressure vessel welds, defect lengths are not to exceed 1.8 t (wehre t is the material thickness of the thinnest member being joined). This stratagem approaches the maximum

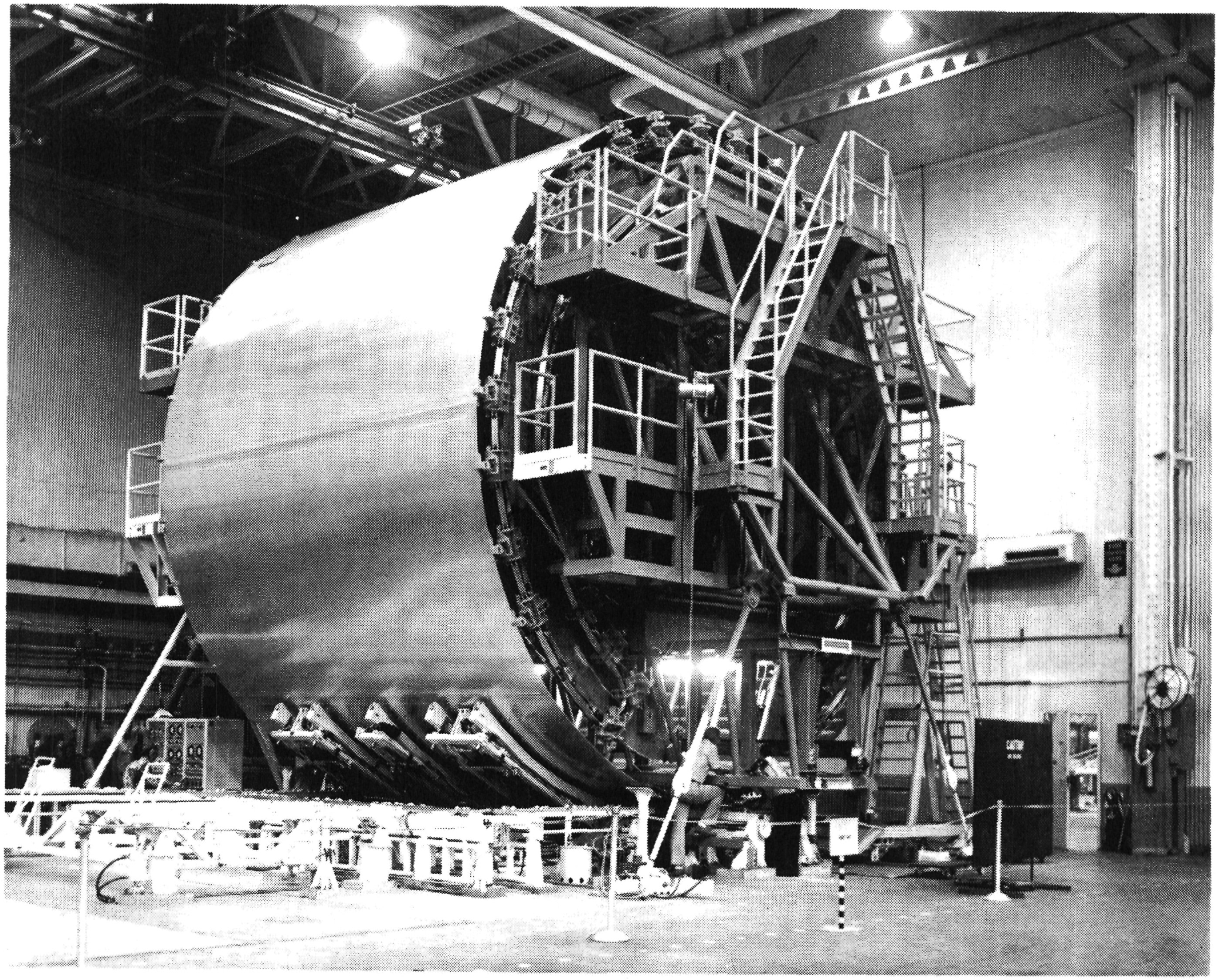

Figure 7. LH_2 barrel trim-and-weld fixture.

manufacturing leeway permissible and minimizes the cost and tank weight without compromising ultimate reliability.

B. ET Thermal Protection System Considerations

The ET Thermal Protection System (TPS) is designed to maintain the primary structure and its subsystem components within design temperature limits during prelaunch and ascent phases. It currently consists primarily of two types of sprayable material to meet a variety of mission and surface application conditions. One protects primarily by insulating and the other by ablating. Although both TPS materials used on the ET are sprayable, both can be used premolded for certain applications such as closeouts. The TPS system also includes the use of phenolic insolator blocks and cryopumped argon-jacketed feed and recirculation lines. Prior to launch, the TPS maintains consistent LOX and LH_2 boiloff rates within the vent valve capabilities, helps loading accuracy and propellant density, minimizes air liquification and ice formation on the LH_2 tank, and insures LOX and LH_2 specified temperatures on the Orbiter surface. During ascent, the TPS maintains the primary structure and subsystem components within the design temperature limits and it minimizes unusable LH_2. The types, areas, and thicknesses of the TPS materials are based primarily on worst-case environments which can only be encountered in the case of an abort-once-around condition.

The Shuttle ET TPS flight environment is a more severe one than the Saturn V stages experienced; temperatures in general are higher. Saturn V foam insulation was a polyurethane material, while the ET foram is a fluorocarbon-blown-rigid polyisocyanurate foam. This foam compares favorably with polyurethane foam regarding density and thermal conductivity, and although tensile strength is somewhat less, the polyisocyanurate foam can withstand greater heating and greater aerodynamic shear and has superior thermal stability. The foam is entirely cryo-strain compatible. A chromate inhibited epoxy primer is applied over the Iridite coated 2219 material before spraying the foam. The foam is net-spray applied (no machining to contour) at 125 ± 5°F (325 ± 3 K) and at a maximum relative humidity of 60 percent. A silicone cover coat is then used to cover the net-sprayed foam. The spraying of the foam insulation is carried out under very carefully controlled process conditions. Figure 8 shows the "processing feasibility box" developed by extensive processing testing. This chart gives the permissible limits of temperature and humidity of successful

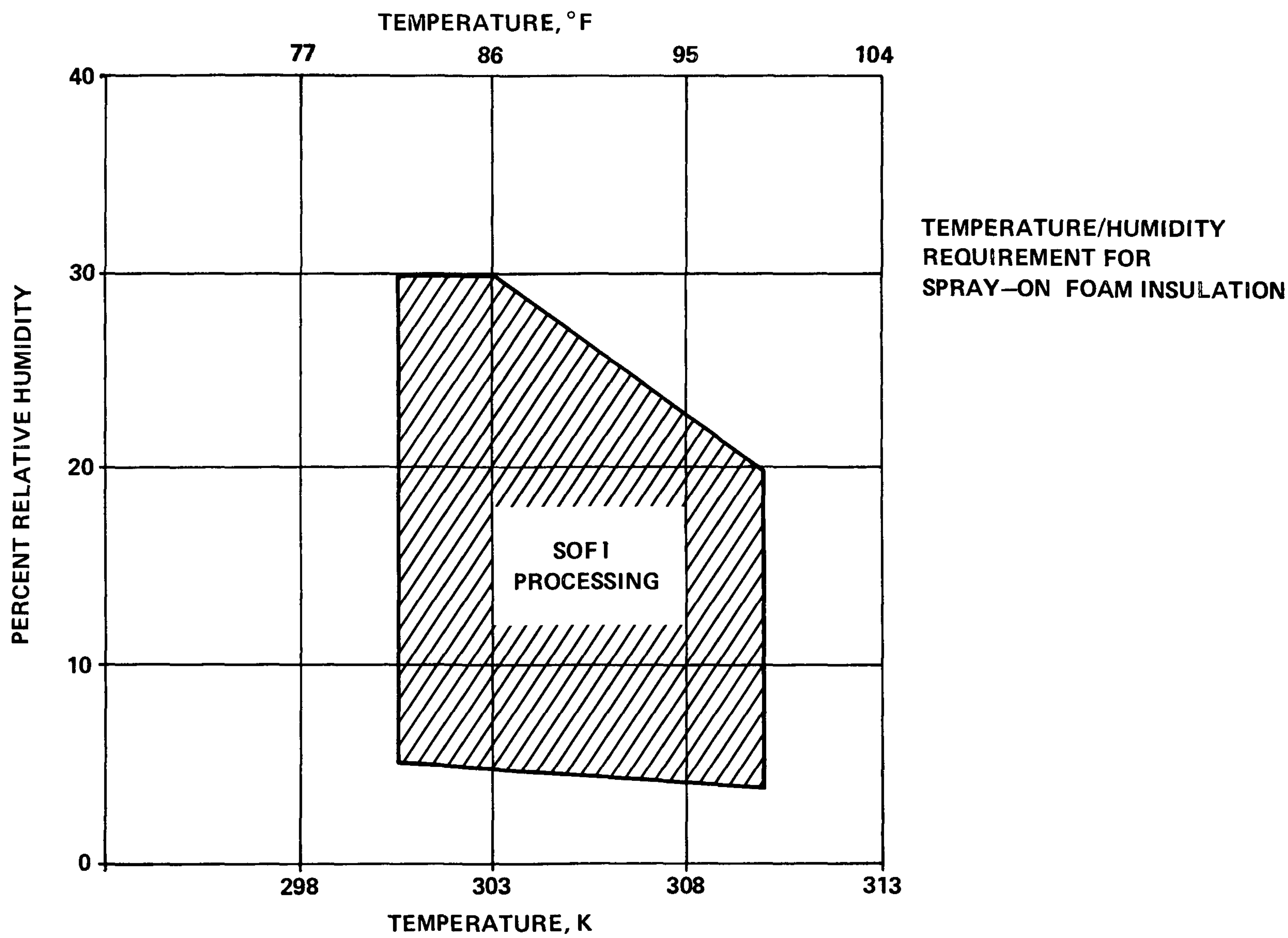

Figure 8. SOFI facility capability at Michoud Assembly Facility.

spray application of the polyisocyanurate foam to the ET. The processing facility at the plant in Michoud, New Orleans, has been designed to maintain processing conditions well inside the feasibility box noted in Figure 7.

Above a heat flux of approximately 6 Btu/ft^2/sec (68.1 kW/m^2), a more dense, ablating type material is required. Shock impingement resulting from interference contours causes interference heating in certain specific areas. While spray foam predominantly covers the forward LOX tank, the intertank structure and the aft hydrogen tank, there is a requirement for the ablative type material on the nose cap, the ET-to-Orbiter attachments, the external LOX and LH_2 tank tray cabling, under the external GOX and LOX lines, and on the intertank where the Orbiter shock wave impinges. The sprayable ablator material, SLA 561S, has a silicone resin matrix with low and high density fillers according to function, consisting of cork and silica microspheres and microballoons, and silica glass fibers and carbon powder. Table 7 gives the properties of the primary and alternate spray foam, and properties of the prime ablator candidate. The ablator material is applied to the Iridited surfaces which have been previously prepared with a chromate/epoxy corrosion protective coating, a silicone primer, and a polysiloxane adhesive coating. The ablator can be sprayed, or molded, and adhesively bonded in place as noted earlier. The external surfaces of the applied ablator are sealed with a spray-applied silicone coating. The spray foam insulation and the ablator material are nonstructural from an overall load carrying point of veiw, but both are designed and fabricated to withstand the aero/thermal and induced load stresses without impairing thermal efficiency.

V. SRB MATERIALS AND PROCESSES

The SRB element of the Space Shuttle is composed of six subsystems: the Solid Rocket Motor (SRM), the structural subsystem, the thrust vector control (TVC) subsystem, the mechanical and ordnance equipment subsystem, the recovery subsystem containing the mechanical and parachute equipment, and the electrical subsystem including the range safety system. All elements except the nose cap and separation motors are intended to be reusable and are recovered via pilot, drogue, and main chutes.

The SRM is the primary propulsive element, providing impulse and TVC from ignition to SRB staging. The SRM consists essentially of a lined, insulated,

TABLE 7. ET/TPS MATERIALS

Type	Polyisocyanurate Foam No. 1	Polyisocyanurate Foam No. 2	Ablator-Filled Silicone
Density			
lb/ft^3	2.3 ± 0.3	2.3 ± 0.3	17 ± 2
(kg/m^3)	(36.8 ± 4.8)	(36.8 ± 4.8)	(272.3 ± 32)
Form	Spray	Spray	Spray
Thermal Conductivity, K			
Btu-in./hr-ft^2-°F	0.15	0.15	0.50
(W/m-K)	(0.022)	(0.022)	(0.072)
Heat Flux, Radiant			
Btu/ft^2-sec	10	8 - 10	
(kW/m^2)	(113.5)	(90.8 - 113.5)	
Heat Flux/Aeroshear			
Btu/ft^2-sec	6 - 8	6 - 8	20
(kW/m^2)	(68.1 - 90.8)	(68.1 - 90.8)	(227)
Coefficient Expansion			
in./in.-°F	7×10^{-5}	7×10^{-5}	0.98×10^{-5}
(m/m-K)	(12.6×10^{-5})	(12.6×10^{-5})	(1.76×10^{-5})
Temperature Range, °F	0 to +200	0 to +200	-200 to +200
(Temperature Range, K)	(255 to 366)	(255 to 366)	(144 to 366)

TABLE 7. (Concluded)

Type	Polyisocyanurate Foam No. 1	Polyisocyanurate Foam No. 2	Ablator-Filled Silicone
Flatwise Tensile Strength, psi (MPa)			
-300°F (422 K)	35 - 60 (0.24 - 0.41)	25 - 45 (0.21 - 0.31)	460 - 600 (0.24 - 4.14)
75°F (297 K)	40 - 70 (0.28 - 0.48)	30 - 55 (0.21 - 0.38)	35 - 55 (0.24 - 0.38)
300°F (422 K)	20 - 40[a] (0.14 - 0.28)[a]	15 - 35 (0.1 - 0.24)	30 - 45[a] (0.21 - 0.31)[a]
500°F (533 K)			20 - 35[a] (0.14 - 0.24)[a]

a. Data range estimate.

segmented weldless D6AC steel rocket motor case loaded with TP-H1148 propellant which is a composite type solid propellant formulated of polybutadiene acrylic acid acrylonitrile terpolymer binder (PBAN), ammonium perchlorate, and aluminum powder, with a small amount of iron oxide burning rate catalyst. An ignition system, initiators, igniter, movable nozzle, raceway, and instrumentation are other essential parts of the SRB.

Performance interchangeability and replaceability between a flight set of SRM's for the SRB can be maintained by matching the burning rates of motor segments cast in matched pairs from the same propellant lot. The sea level thrust of the SRM will be 2.65 million lb (11.8 Mkg). The propellant grain design is performance tailored, consisting of a forward segment with an 11-point star and transitioning into a cylindrical perforated configuration in the cylindrical portion of the segment, two identically configured center segments that are tapered cylindrical perforated and an aft segment with a dual taper cylindrical perforated configuration. Figure 9 gives SRB subsystem and propellant configuration detailed information.

The 11-point star configuration in the forward segment produces high level liftoff thrust until burnout of the star sliver, within approximately 52 sec. Burning of the cylindrical perforated configurations continues until thrust decay due to burnout of the aft-most portion of the aft segment. A linear 10 sec thrust decay is achieved by the programmed burnout of slivers in all four segments.

The insulation used in the chamber, the propellant relief flaps, and the forward inhibitors are asbestos-silica-filled nitrile butadiene rubber (NBR). The aft inhibitor insulation material is an asbestos-filled carboxyl terminated polybutadiene polymer (HC polymer). The inhibitors typically are designed to prevent ignition and burning of the propellant grain in a direction perpendicular to the inhibitor surface. The case liner material is an asbestos-filled CTPB polymer (UF-2137).

The SRM nozzle is a convergent divergent movable design containing an aft pivot point flexible bearing as the gimbal mechanism. This type of bearing has been used previously in the Poseidon missile; however, the SRM nozzle and flexible bearing are larger than any others in current use.

Throughout the design and development of the SRB, recovery and reuse have been the prime design drivers. A number of new situations never before faced by aerospace designers have arisen. In fact in the areas of recovery and

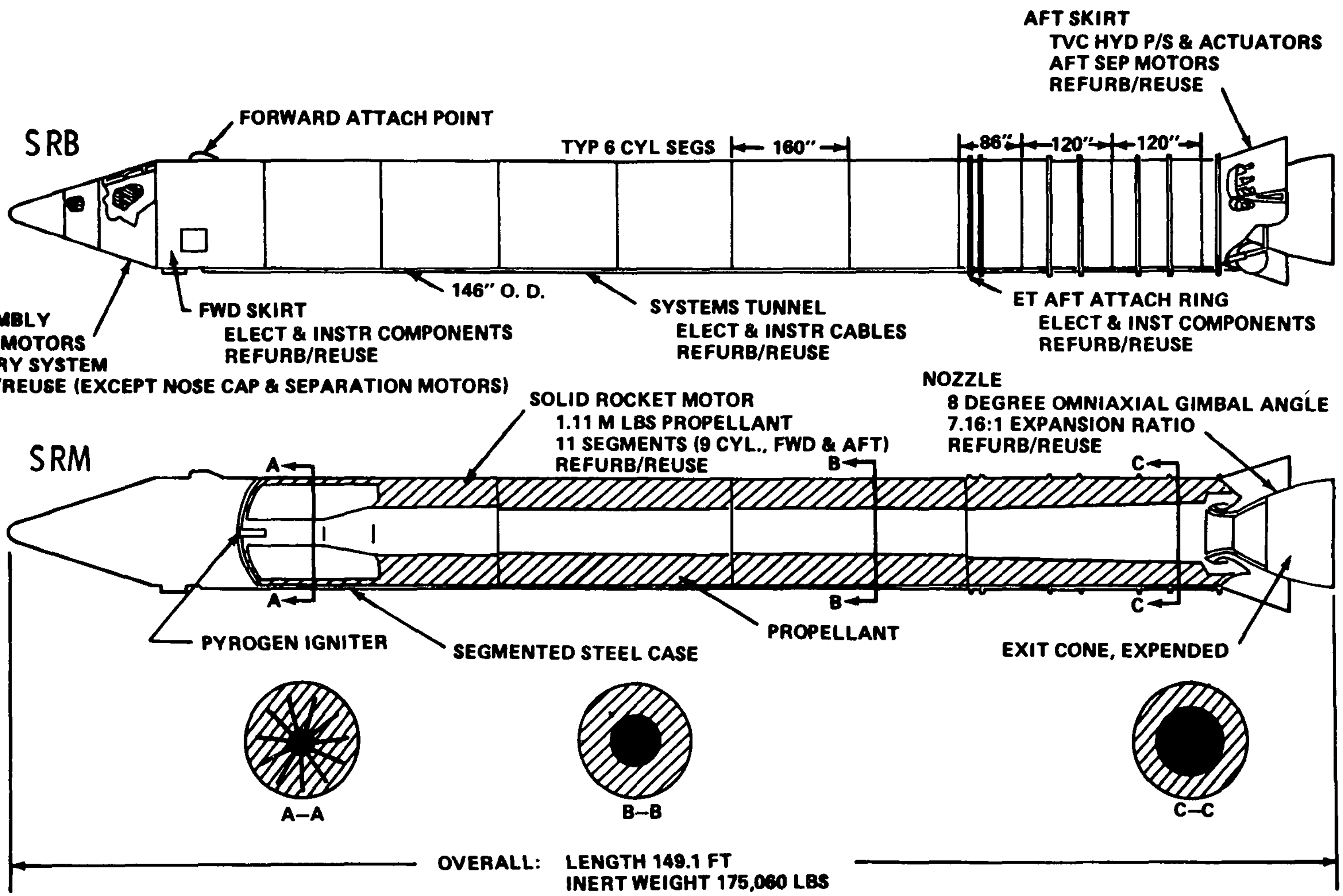

Figure 9. SRB/ SRM.

reuse of subsystems, the engineering shop talk has been frequently more reminiscent of a Navy shipyard or a dockside marina, with frequent discussions on estuarine corrosion, splash zone corrosion, salt water enhanced crack growth, and a host of other marine related considerations. Even the ravages of marine biological attack had to be considered because under conducive conditions some undesirable forms of biological attachment can begin within hours. As a consequence, materials were selected very carefully. Table 8 presents a wide range of metallic materials and associated applications which are used in the SRB.

The driving impetus of reusability provided many of the unique challenges. A few of the more salient materials and processes challenges and resolutions to those challenges will now be discussed.

A. Engineering to Prevent Corrosion

One of the most seemingly incongruous intentions in the whole Shuttle element recovery scheme is the idea of dropping the steel/aluminum SRB's in the ocean, and then subsequently reusing them. The D6AC steel used in the motor case elements is a medium carbon (0.42 to 0.48 percent), low alloy ultrahigh strength steel, which is electric furnace air melted and remelted by the vacuum consumable electrode process (denoted by the addition of "C" to the D6AC designation). The rusting of unprotected D6AC steel in saltwater is rapid and uniformly aggressive. Although the selection of D6AC for the SRM motor case was sound from a design and an econometrics point of view, it placed much responsibility on the corrosion engineer. Weekend sailors and others well acquainted with the aggressiveness of the marine environment can comprehend the full significance of recovery from the ocean, refurbishment, and reuse of the SRB's.

In the corrosion engineering assessment of the SRB, several marine environments were considered: atmosphere, splash zone, tidal zone, and immersed condition. The many corrosion tests conducted were designed to evaluate potential materials under the aggressive conditions expected in the use-recovery-refurbish-reuse cycle of the SRB. In the corrosion testing, factors affecting corrosivity in seawater such as biological activity, oxygen availability, water temperature, water velocity, salinity, and pH were considered. Specific forms of corrosion considered in the design of the corrosion protective materials arrangements included galvanic corrosion, crevice

TABLE 8. SPACE SHUTTLE SRB METALLIC MATERIALS

Material	Application	Material	Application
2219/2419	Systems tunnel Forward skirt Aft skirt Frustum structural assembly Forward ordnance ring Forward skirt Aft Skirt	5052 Aluminum	Systems tunnel Aft ring Forward skirt
		1100 Aluminum	Systems tunnel
		AL Shim Stock	Pendant assembly towing
2024	Nose cap	Alclad	Frustum structural assembly Nose cap
6061	Data capsule assembly Pendant assembly Frustum — secondary structure Forward ordnance ring Forward skirt — cable	Inconel	Pendant assembly towing Forward skirt Aft ring
		MP 35N	Frustum structural assembly Forward skirt Aft skirt
A 286	Pendant assembly Data capsule assembly Systems tunnel Nose cap Frustum structural assembly Forward ordnance ring Forward skirt Aft skirt Aft ring	18-8 CRES	Forward skirt
		Steel Wire, QQ-W-470	Data Capsule assembly
		CRES Wire, MIL-W-460718	Systems tunnel
		D6AC Steel, Roll Forged	Aft skirt
300 series steel	Data capsule assembly Frustum structural assembly Forward skirt Systems tunnel	Forged Carbon Steel, Zinc Coating (NAS 1053-04-16 modified)	Pendant assembly towing
17-4 PH H1025	Data capsule assembly	Brass, Cadmium Plated (MS 20230BPS2 modified)	Pendant assembly towing
13-8PH H1000	Aft skirt	Expanded Polystyrene Foam per MIL-P-40619, Class 2, Grade A, Formed by the Expansion and Fusion of Polystyrene Beads	Frustum flotation blocks
4340	Systems tunnel Aft ring		

corrosion, pitting corrosion, impingement corrosion, and cavitation corrosion. Only the first three forms of corrosion are considered important in the SRB application because the recovery towing speeds are relatively low.

Bare D6AC steel corrosion is controlled largely by the reaction at the cathode, while bare 2219 aluminum corrosion rate is influenced primarily by the formation of a passive oxide film. The practical implications of this behavior are that the bare D6AC will exhibit high corrosion rates in the splash zone where O_2 is plentiful, and bare 2219 aluminum will be especially susceptible to crevice corrosion and pitting in stagnant seawater conditions because the formation of the protective oxide is impeded by the limited availability of O_2. The latter effect is sometimes referred to as a differential aeration cell effect. The presence of copper in the 2219 aluminum alloy also enhances the probability of pitting due to the availability of heavy metal ions. Obviously good surface protection is mandatory.

In recognition of these challenging corrosion engineering requirements, a comprehensive series of tests was accomplished between February 1972 and July 1976 in the Gulf of Mexico and in the Atlantic Ocean in the vicinity of Cape Canaveral. Table 9 depicts the Gulf and Canaveral locations, some of the test materials and protective coatings, and some of the test modes. In addition to these tests, flowing seawater and alternate immersion tests were conducted. The results give confidence that adequate protection can be provided the SRB's, sufficient to allow the scheduled 20 uses per SRM case segment and 40 uses for the SRB structure. Based on these results, the following protective coatings and TPS material appear most probable for use at this time:

Forward SRB/ET attach fitting-2219 Al and aft ET attach ring-4340 steel:

Primer — Zinc Sele No. 9334 (Rustoleum) 2 part epoxy-polyamide, converted resin (90 percent zinc in dried film)

Topcoat — No. 9392 white epoxy polyamide, 47 percent titanium dioxide pigment (Rustoleum)

2219 aluminum skirts:

Surface Treatment — Alodine 1200 conversion coating

TABLE 9. OCEAN ENVIRONMENT SRB MATERIALS TESTS

Date	Location	Materials	Coatings	Sealants	Test Mode
1. Feb. 1972	Gulf (7 days)	• 2219-T8	Bare, epoxy, anodize, alodine	None	Rack and tower
		• Inconel 718	Bare	None	
		• Ti-6Al-4V		None	
		• Couples of above		None	
2. July 1972	Gulf (24 and 72 hr)	• D6AC	Bare and epoxy zinc rich	None	3 and 12 mile tower
		• 4130	Bare		
		• 18 Ni Maraging	Epoxy chromate		
		• HY-140	Epoxy chromate		
		• 2219-T87	Epoxy chromate		
		• 6061-T6	Epoxy chromate		
3. Feb. 1974	Gulf (5 days and 100 days)	• HY-140	(1) Bare, (2) galvanized; (3) galvanized + epoxy zinc, (4) galvanized + epoxy zinc + silicone sealant		12 mile tower
		• 2219-T87	Bare; epoxy		
4. Sept. 1975	Canaveral (7 days ocean +3 Banana River)	• 2219-T87	Bare; epoxy chromate		Rack at splash level
		• 7075-T651	Bare; epoxy chromate		
		• D6AC	Bare; epoxy zinc rich		
		• Couples of above with 7 polysulfide and 1 silicone			
		• Clevis joint specimens	D6AC and 2219-T87 Bare, corrosion preventative coating		Rack at splash level
5. July 1976	Canaveral ITB Test (7 days ocean + 3 days Banana River)	• D6AC	Epoxy zinc rich		Floated 80% immersed
		• 2219 } • 7075 }	Epoxy chromate		
		• Insulations 1. MXSA sprayed 2. Silicone, bonded 3. Cork, bonded			
		• Clevis joint — painted with preservative and retainer band			

Primer — Bostik/ Finch No. 463-6-3, 2 component epoxy-amine calcium chromate inhibited

Topcoat — Bostik/ Finch Cat-A-Lac Epoxy No. 443-3-1 epoxy-amine, titanium dioxide pigment

SRB TPS:

Coalesing Agent — Epoxy-modified polyurethane resin, Crest 7344

MSA-1[5] — Composition: BJO microballoons (phenolic) and glass eccospheres, chopped and milled glass fibers, end capped Epoxy-polyurethane resin, Crest 7119 accelerator, methylene chloride and perchloroethylene thinner, Bentone 27 suspension agent with ethyl alcohol activator.

Topcoat — White pigmented butadiene/ styrene with methylene chloride/ perchloroethylene solvent.

The ability of these coatings to provide adequate protection is of paramount importance, as is shown in the next section on stress corrosion.

B. The Stress Corrosion Ogre and Fracture Toughness

As noted earlier, D6AC steel corrodes relatively readily. Not unexpectedly, it is also susceptible to SCC, having a sustained tensile stress threshold of one-half the yield strength, or approximately 90 ksi (621 MPa), as determined by 3.5 percent sodium chloride solution alternate immersion tests. In actual use, the SRB could be subjected to sustained tensile stresses due to assembly, storage or handling peculiarities, and wind loads on the launch pads, but estimation of these stresses indicates that the aggregate will be well below the threshold stress of 90 ski (621 MPa). Hence, there is no reasonable probability that environmentally initiated SCC of the type previously encountered in certain aluminum alloy launch vehicles will occur. However, the possibility of environmentally enhanced growth of preexisting flaws must then be given serious consideration.

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5. Marshall Sprayable Ablator No. 1.

Preexisting flaws in the D6AC steel will be sought out by meticulous application of ultrasonic and magnetic particle inspection of raw materials, forgings, and machined case segments. Further, each case segment will be proof tested before each use, and magnetic particle inspection will be used before and after proof. The flaw detection capability is approximately 0.100 by 0.050 in. (2.53 by 1.27 mm) with a probability of detection 0.915 at a confidence level of 99 percent. Tests on an actual clevis joint which joins the case segments have verified this capability. By this means, flaws which have the propensity to grow to critical dimensions (size where unstable propagation results) will be detected before hand. The critical flaw size is a function of stress and the fracture toughness, K_{1c}, of the D6AC material. The SRM case segments will be heat treated to a K_{1c} of at least 90 ksi $\sqrt{\text{in.}}$ (98.9 MN/$m^{1.5}$). However, should a flaw with the potential to grow critical during the very next use-cycle of the case go undetected, it will be found during the hydroproof of the case segment.

The flaw detection system is almost foolproof — except for one possibility, i.e., the possibility of environmentally enhanced flaw growth after hydroproof in the subsequent period of storage, handling, pad time, and the relatively short flight service period. To assess the implications of this relatively long term, environmentally enhanced, flaw growth possibility, a knowledge of K_{1scc} is required — the fracture toughness of the D6AC material in the presence of a SCC environment. Analysis and testing are in progress to insure that either flaw sizes acceptable on the basis of K_{1c} (benign environment) do not grow to critical size due to the presence of a SCC environment, or that if smaller flaw sizes must be detected, they can be.

For the vast majority of the SRB structural elements, the amount by which the proof stress exceeds the operating stress provides sufficient margin for only subcritical flaw growth; that is, no flaw surviving proof can subsequently grow to fracture critical size either before or during the flight. But four specific areas are receiving special attention: clevis joints, case membrane at aft end side toward ET/SRB attach point, the forward and aft "Y" joint, and the membrane of the forward and aft closures. To exonerate these areas, new precise data on K_{1scc} are being developed using authentic SRM materials which are heat treated according to the exact SRM schedule to be used for the flight vehicle. These data are being used in conjunction with special measured data on manufacturing stresses, assembly stresses, and calculated wind loading stresses to determine what improvement in flaw size detection, if any, will be required in these four areas where proof test alone is inadequate, regarding the slight possibility of environmentally enhanced flaw growth. The fracture toughness in a stress corrosion environment is appreciably lower than the standard benign environment fracture toughness, or K_{1c}. Values for D6AC K_{1scc} can be found in the literature ranging from 16 to 30 ksi $\sqrt{in.}$ (17.6 to 33 MN/$m^{1.5}$). As noted previously, analysis and preliminary data indicate that nondestructive evaluation techniques can be applied which will allow the detection of the even smaller flaw sizes associated with K_{1scc} values in the low end of the range, should that prove necessary. The determination of the role of the SCC environmentally induced flaw growth is a precaution not previously considered with "one-shot" solid rocket cases: The requirement for reuse makes the K_{1scc} assessment necessary. It is important, however, to remember that for environmentally enhanced flaw growth to occur in the first place a breakdown in the protective coatings must occur. As noted in the discussion of engineering to prevent corrosion, excellent sacrificial, tenacious coatings have been prescribed for use on the D6AC, and the probability for inadvertent exposure to the corrosive environment is low. However, in any case no stone has been left unturned to assure sustained adequate fracture toughness throughout the life cycle of the SRB.

C. In-Situ Corrosion Protection Verification — The Integrated Test Bed

As previously noted, the requirement for economical reuse has been the predominant influence in the selection of materials for the SRB. This has been most apparent in the case of materials selection for corrosion protection. As noted in the previous discussion entitled "Engineering to Prevent Corrosion," a number of sample material tests were completed during the period of February 1972 through July 1976 in the Gulf of Mexico and in the Atlantic Ocean. Various metal alloy and protective coating specimens were tested under a variety of exposure conditions designed to run the gamut of expected SRB exposures conditions.

The results of these preliminary tests determined the material selections for the integrated test bed (ITB). The ITB is an almost-full-scale [10 by 8 ft (3.05 by 2.44 m)] simulation of the 12 ft (3.66 m) diameter SRB frustum, which has been prepared using the currently most promising candidate materials. The prime ablator material MSA-1, and backup cork and silicone materials were used as were zinc rich primer coating topcoats. A modified styrene butadiene rubber coating material with a carbon black pigment and one with a titanium dioxide white pigment were tested. This material has promise for use as a moisture resistant overcoat for the MSA-1 ablator material and also as a "cummerbund" around the clevis joint elements of the solid motor case segments. The clevis joint requires the cummerbund overlay to prevent seawater from entering the clevis joint where corrosion could continue even after the SRB had been removed from the sea. An earlier design concept envisioned a 7 in. wide cummerbund of ethylene-propylene rubber, spanning the parting line of the joint, held in place by a circumferential stainless steel retainer strap at each end of the cummerbund. The current concept consists of a modified styrene butadiene material either painted or sprayed over the clevis joint. This material was proven in the ITB tests to be completely watertight and can be cleanly stripped from the joint with only moderate effort.

Interior frustum floatation foam and methods of quick removal of floatation foam were also tested in the ITB test. Figure 10 shows the ITB being taken under tow in the Atlantic Ocean off Cape Canaveral. The results of the ITB test have been excellent, and it is evident that the materials used in the ITB test now constitute a baseline set of materials adequate for environmental protection during recovery and for the refurbishment activity. In actual use, the ablative material will have to be removed during the refurbishment activity; therefore, some inordinately tenacious materials and coating combinations had to be eliminated from consideration. The MSA-1 ablator material can be readily removed by a "Hydro Laser" machine which employs a 5000 to 7000 psi (34.5 to 48.3 MPa) jet of water to remove the material. Because of the associated adhesives and softeners, some other materials (e.g. silicone) are extremely difficult to remove by Hydro Laser.

Open ocean and Banana River exposure was provided in the ITB test series. As a result of this exposure, considerable biological attachment was evident on the test bed. When a metal or other surface is first immersed in seawater, a biological slime develops in a matter of a few hours. This slime is a prerequisite to the attraction and attachment of sessile fouling organisms

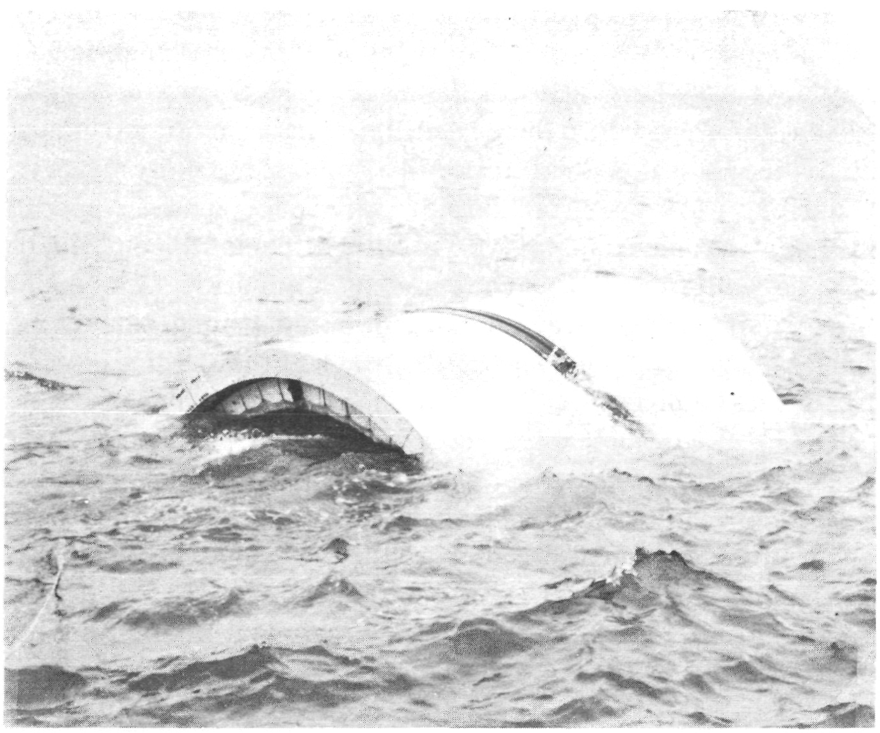

Figure 10. The ITB which simulates the SRM frustum, being taken under tow in the Atlantic Ocean off Cape Canaveral.

which, once attached, rapidly transform to the mature form and become immobile. The initial supposition that the relatively short periods of exposure during recovery would constitute inadequate time for biological growth to begin has not proved accurate. Special cleaning techniques are being developed to strip the SRB of slime and the embryonic fouling organisms. Even if the exposure time has only allowed the formation of the prerequisite slime, the slime itself is highly hygroscopic and retains a high percentage of moisture and salt when an object is removed from the water. This aids and abets general corrosion of the metallic materials. The SRB will experience optimum corrosion conditions for steel and aluminum, but at different times, in the recovery sequence. In the splash zone and open sea, steel corrosion will be enhanced due to the oxygen rich environment which provides ready depolarization of the cathode and greatly aids local action corrosion. Aluminum, however, rapidly builds a protective passive film or layer in the presence of abundant oxygen, but in areas such as bays, estuaries, and rivers the corrosion of aluminum is accelerated where the oxygen supply to the metal may be restricted. These factors have all been considered in the design and selection of materials for the recoverable SRB. Noteworthy accomplishments have not been confined to design alone. Some outstanding processing improvements have been incorporated in the SRB development; an example is presented in the next section.

D. 2219 Aluminum Processing Breakthrough

The SRB aft skirt and forward frustum design utilizes 2219 aluminum alloy in the T87 heat treated temper. These SRB elements are composed of forgings, extruded shapes, and heavy plates which are machine milled into pocketed or ribbed patterns. These components are subsequently welded together to comprise the large rigid structures (Fig. 9). The forward frustum is just aft of the nose cap, and part of the nose assembly and the aft skirt can be seen all the way aft.

The aft skirt in particular has a high strength requirement to survive the parachute plunge into the ocean, stern first. The momentum of this plunge will carry the aft end of the SRB to a depth of 80 ft (24.4 m). This water entry requires a skirt structure of rigid construction, and the associated loads are the predominant design driver. Further, as previously noted, the structural parts of the SRB must allow 40 uses. To provide the many reuses required, the aft skirt design became very sturdy and required welding of heavy 2219 sections. This prospect caused much concern about welding distortion, residual stresses, and lowering of strength due to the effect of welding thick sections.

As a result, a test program was initiated in which 2219-T37 aluminum alloy was welded and then restrain aged to the T87 temper by heat aging at 350°F (394 K) for 18 hr. The results were quite spectacular. Weld distortion was virtually eliminated, yield and ultimate strength were typically improved approximately 10 percent and 20 percent, respectively, and the consistency of improved properties over a wide range of material thicknesses was quite remarkable. Figure 11 shows a typical stress-strain curve for 3/4 in. (19.05 mm) TIG welded aluminum plate, as-welded, and welded-and-aged at 350°F (394 K) for 18 hr. The dramatic improvement in properties is readily apparent. The fact that the welded-and-aged stress strain curve for 1/4 in. (6.35 mm) and 1/2 in. (12.7 mm) material practically coincides with the welded-and-aged curve for 3/4 in. (19.05 mm) material is significant. This shows the efficacy of the weld and restrain age technique in acquiring uniformly high and consistent

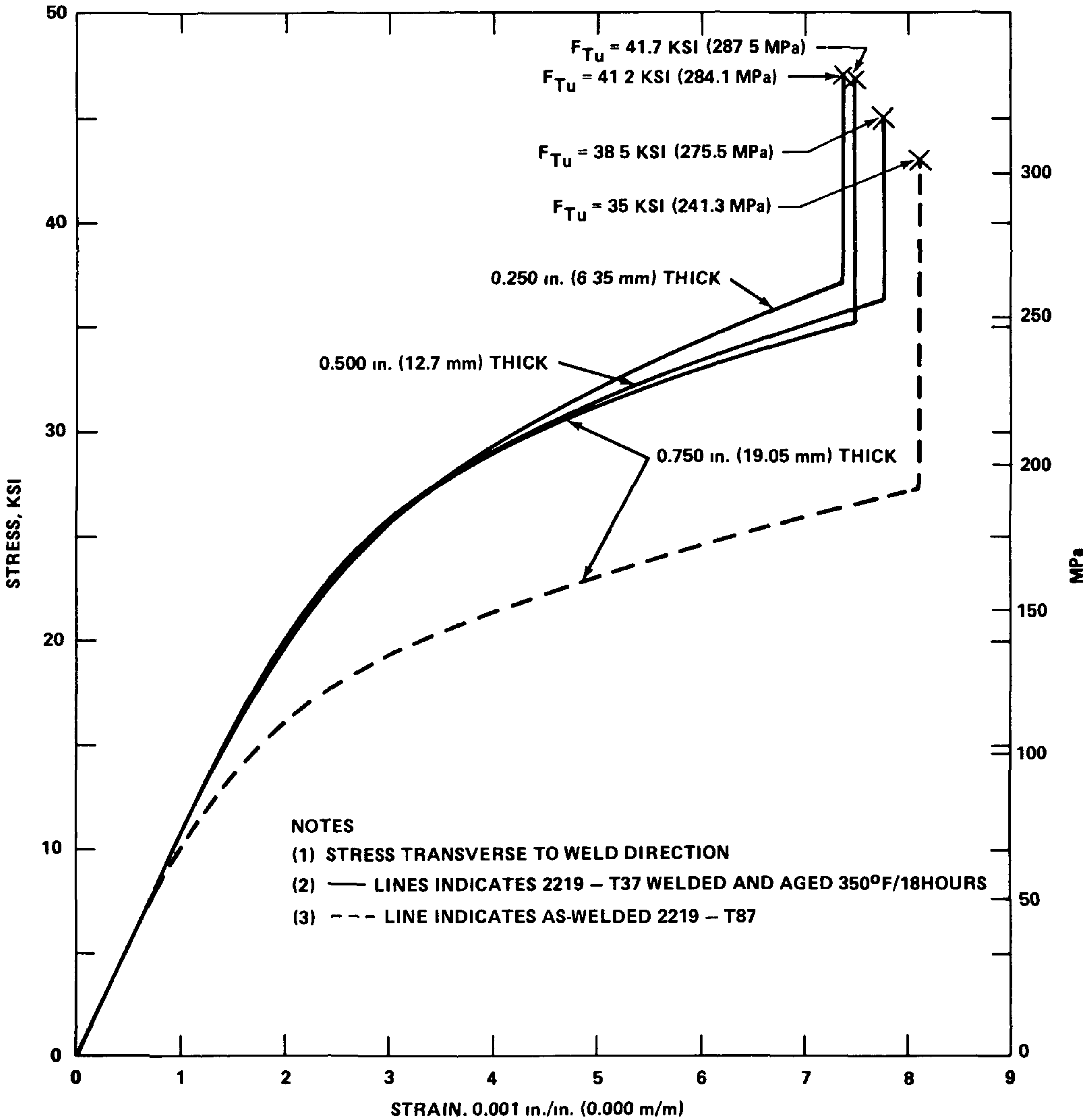

Figure 11. Typical stress strain curves of 2219 aluminum plate, 3/4 in. (19.05 mm) thick, weldments (TIG process).

properties throughout the entire skirt structure. By restraining the welded structure to the designed contour during the heat aging cycle, nearly all weld distortion can be removed. It naturally follows then, that the welded assembly fabricated by this method has very low residual stresses and is easy to produce to specified tolerances. This is important for good fit-up of mating parts, which in turn guarantees low assembly stresses. The sum total of this material/ process innovation greatly improves the service life of the SRB aft skirt and the forward frustum, both of which experience the water impact loads associated with ocean recovery.

E. SRB Thermal Protection System

The thermal environment to which the SRB will be exposed in flight requires that a portion of the surface be covered with a high temperature ablator material. A typical heat flux/aeroshear level of approximately 12 Btu/ft^2-sec (136.2 kW/m^2) must be withstood. In 1972, MSFC undertook the development of a material to meet the SRB requirements. MSA-1, a room temperature curing ablator material which is sprayable through standard commercially available spray guns and pumps, evolved. In the interest of expediency in processing, an elevated temperature cure was also developed [150° ± 10°F (3.39 ± 5 K) for 4 hr]. The general composition is as previously noted under SRB TPS-MSA-1

The application of the ablative material to the SRB is baselined as an automated process. The SRB segment to be sprayed will be attached to a turntable, permitting a controlled rate of ablator material application. During spraying, the rotational speed of the turntable, the vertical speed of the spray gun, and the output of the spray equipment are synchronized so that the deposited ablator material is of the required uniform thickness. The surface of the cured insulation exhibits a fibrous overspray (haystack) appearance with a coarse texture that can easily be removed by brushing with a stiff brush. The surface can also be abraded to contour, if necessary. The final operation consists of the application of sealant or topcoat (composition as noted previously).

In the search for the specialized MSA-1 material, cost of material and applied cost weighed heavily. In the testing domain, vibro-acoustic/thermal and aeroshear tests were an essential part of the materials characterization effort. Other candidate materials were also considered; Table 10 gives pertinent properties of some alternate materials. While the MSA-1 material currently has the highest level of maturity and characterization, the option to select one of the alternate materials in the event of any unforeseen impediment still remains.

TABLE 10. SRB/ TPS MATERIALS

Type	MSA-1 Filled Epoxy-Urethane	Silicone Sponge	Cork	Silicone Foam	Filled Silicone
Density lb/ft^3 (kg/m^3)	 17 ± 2 (272 ± 32)	 17 ± 1 (272 ± 16)	 30 ± 2 (481 ± 32)	 17 ± 2 (272 ± 32)	 17 ± 2 (272 ± 32)
Form	Spray	Sheet	Sheet	Spray	Sheet/ Spray
Thermal Conductivity, K Btu-in./hr-ft^2-°F (W/m-K)	 0.55 (0.079)	 0.49 (0.071)	 0.65 (0.094)	 0.54 (0.078)	 0.50 (0.072)
Heat Flux/ Aeroshear Btu/ft^2-sec (kW/m^2)	 13 (148)	 >13 >(148)	 13 (148)	 -	 >20 >(227)
Coefficient of Expansion in./in./°F (m/m/K) Temperature Range, °F (Temperature Range, K)	 1.5×10^{-5} [a] (2.7×10^{-5}) [a] (-200 to +200) (144 to 366)	 14.8×10^{-5} (26.6×10^{-5}) (-150 to +650) (172 to 616)	 2.8×10^{-5} (5.0×10^{-5}) (-65 to +425) (219 to 491)	 0.71×10^{-5} (1.28×10^{-5}) (-13 to +302) (248 to 423)	 0.98×10^{-5} (1.8×10^{-5}) (-200 to +200) (144 to 366)
Flatwise Tensile Strength, psi (KPa) Temperature, °F (Temperature, K)					
-300°F (89 K)	(420 - 500) [a] (2896 - 3448)	86 (593)	(420) [a] (2896)	192 (1324)	460 - 600 (3172 - 4137)
75°F (296 K)	220 - 260 (1517 - 1793)	24 (165)	(90) [a] (621)	26 (179)	35 - 55 (241 379)
300°F (422 K)	(90 - 120) [a] (621 - 827)	16 (110)	(16) [a] (110)	15 (103)	(30 - 45) [a] (207 - 310)
500°F (533 K)	TBD	11 (76)	(10) [a] (69)	7 (48)	(20 - 35) [a] (138 - 241)

a. Data extrapolated.

VI. SUMMARY

Previous launch vehicles have been highly reliable and expendable; however, the Space Shuttle will provide a highly reliable, low cost, reusable launch vehicle system. Reusability, through amortization, lowers the cost. At the same time, reusability has proved to be the prime design driver. To attain the objectives of reusability and low cost, materials and processes selection and tracking are key ingredients which are controlled in the development program. The development of the high performance, variable thrust SSME has challenged the designers and materials engineers particularly in the areas of HEE, LOX/GOX compatibility, and SCC. From these areas, a wide variety of successful materials and process applications have resulted. New data on HEE, LOX/GOX compatibility, and SCC have evolved, which have potential use in a wide variety of applications outside the aerospace field. In the design and manufacture of the ET, significant improvement in 2219 weld quality and reduction in radiographic requirements are being effected. This is primarily the result of the excellent MMC weld tooling and extensive weld porosity testing and weld properties determinations carried out at the MSFC during the late 60's and early 70's. The recoverable SRB provides an impressive challenge to the corrosion engineer, a challenge which is being met successfully through extensive in-situ marine testing. The test effort on the one remaining consideration in the total fracture control picture for the SRB, the possibility of environmentally enhanced growth of preexisting flaws, is well in hand and is not expected to present any difficulty. New techniques of welding and aging the SRB 2219 forward frustum and aft skirt have shown significant improvements in weld properties, with greatly reduced distortion; the soon-to-be-commercialized MSA-1 TPS material for SRB promises to provide appropriate thermal protection and ease of refurbishment. In general, the materials and processes associated with SSME, ET, and SRB development have evolved and progressed in an orderly manner, accompanied by evolution of significant technological data. From the current chronological vantage point, it appears certain that the materials and processes will indeed be equal to the challenging development of the SSME, ET, and SRB.

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